Short-Range Nuclear Structure: Factorization and Interpretation

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Directors' Fellow, Los Alamos National Laboratory

"Light-ion physics in the EIC era"
June 2025, Florida International University, Miami, FL

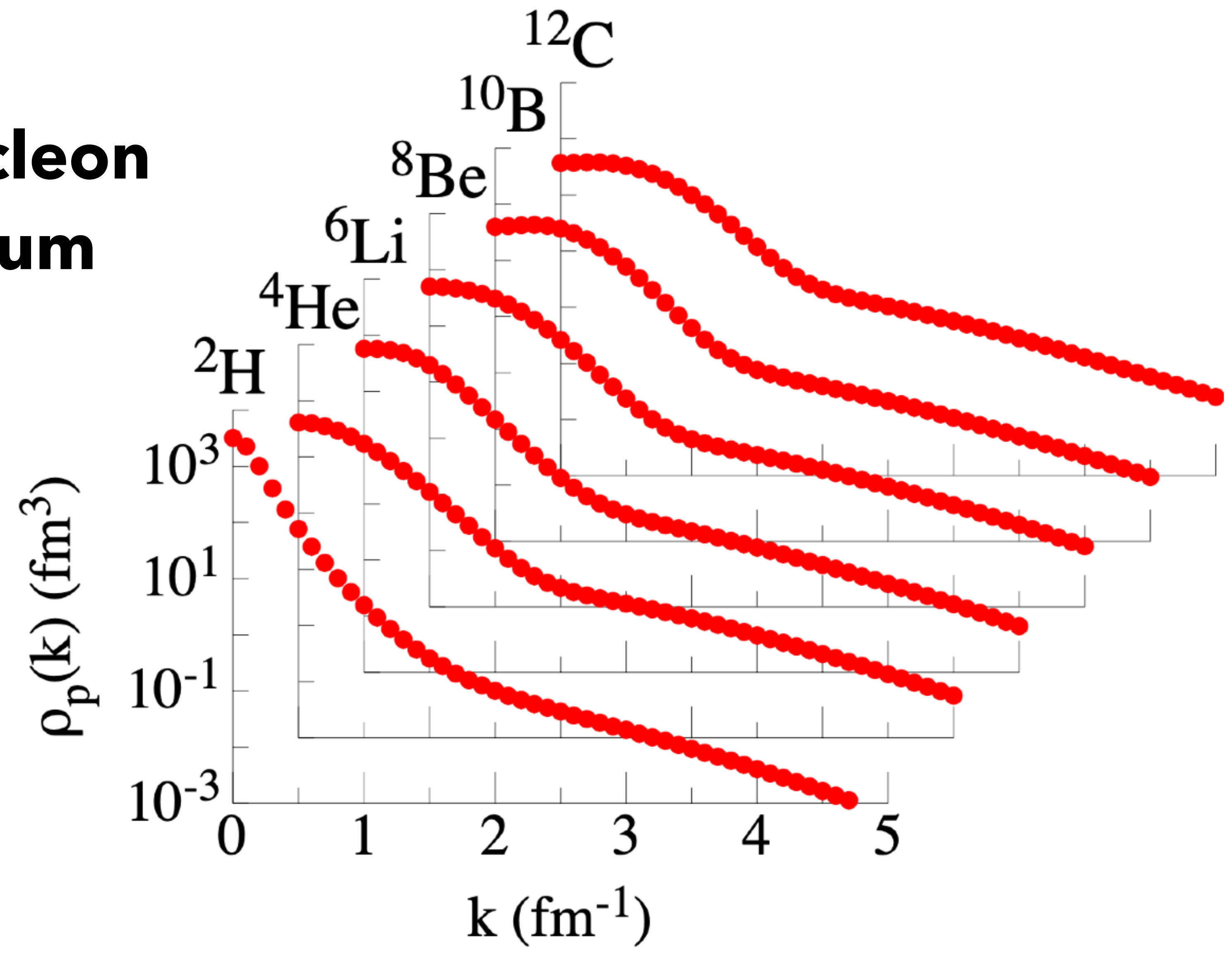
Recap: What we know about SRCs so far

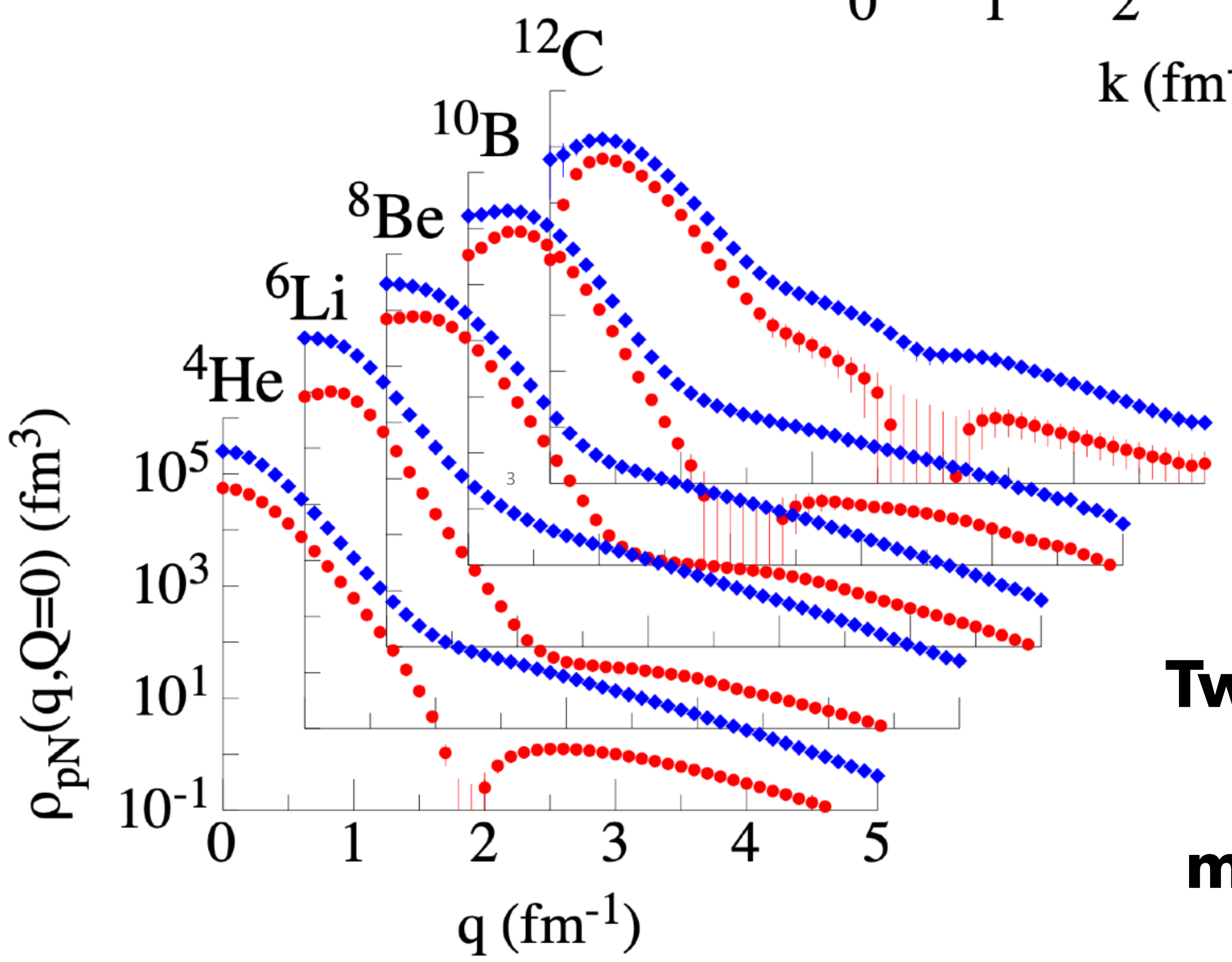
- Short-distance, high-momentum pairs found in nuclei, 10-20% of nucleons
- Studied using high-energy, large-momentum-transfer knockout reactions
- 90% neutron-proton pairs at lower (300-500 MeV/c) momentum
- Abundance and center-of-mass motion increase with *A*

Quantum Monte-Carlo: Another tool to study nuclei

- Provide models of nucleon-nucleon interactions:
  - Phenomenological (data-driven) models like AV18
  - Chiral effective field theory models (N2LO, N3LO)
- Given input NN interaction model, QMC methods can calculate nuclear structure up to $A \approx 12$ (closed shell nuclei up to ^{40}Ca)
- Position- and momentum-space distributions can be extracted to look at pairing behavior

Single-nucleon momentum

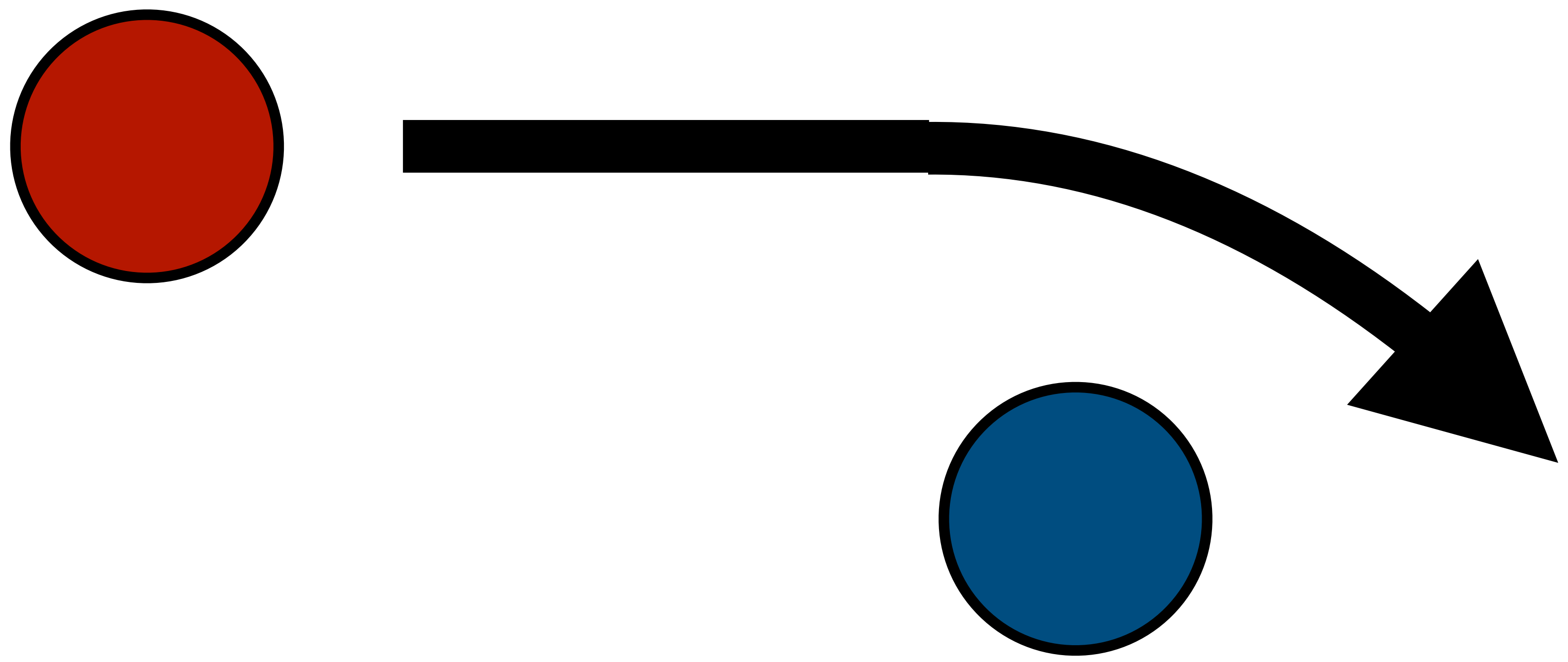




Two-nucleon relative momentum

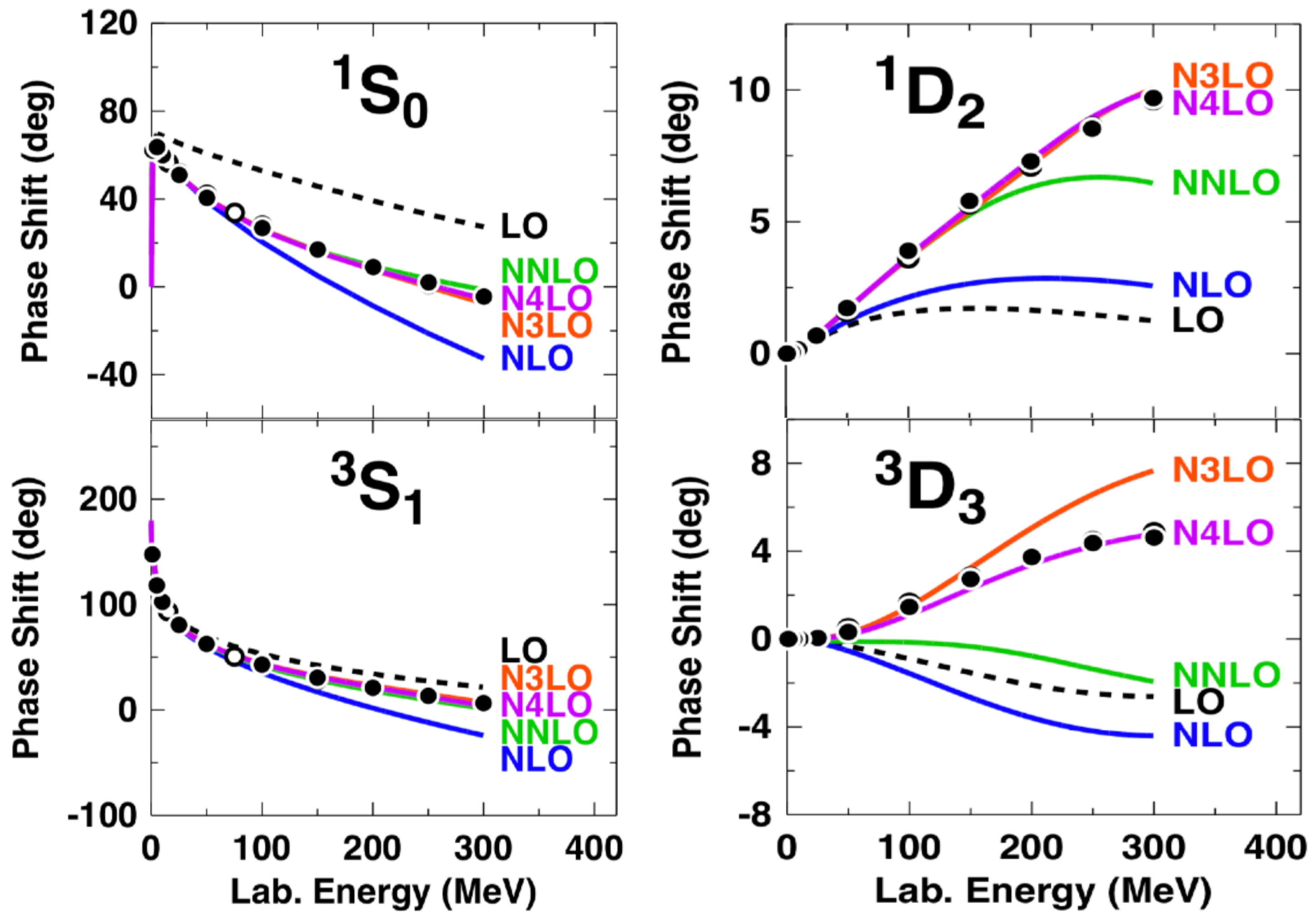
Carlson et al., RMP (2015)

An aside on nucleon-nucleon interactions…



$E_{beam} \lesssim 300$ MeV/c

- NN interactions mainly measured using elastic nucleon-nucleon scattering
  - Partial-wave analysis → determine strength of different components (scalar, tensor, spin-orbit, etc.) at different momentum



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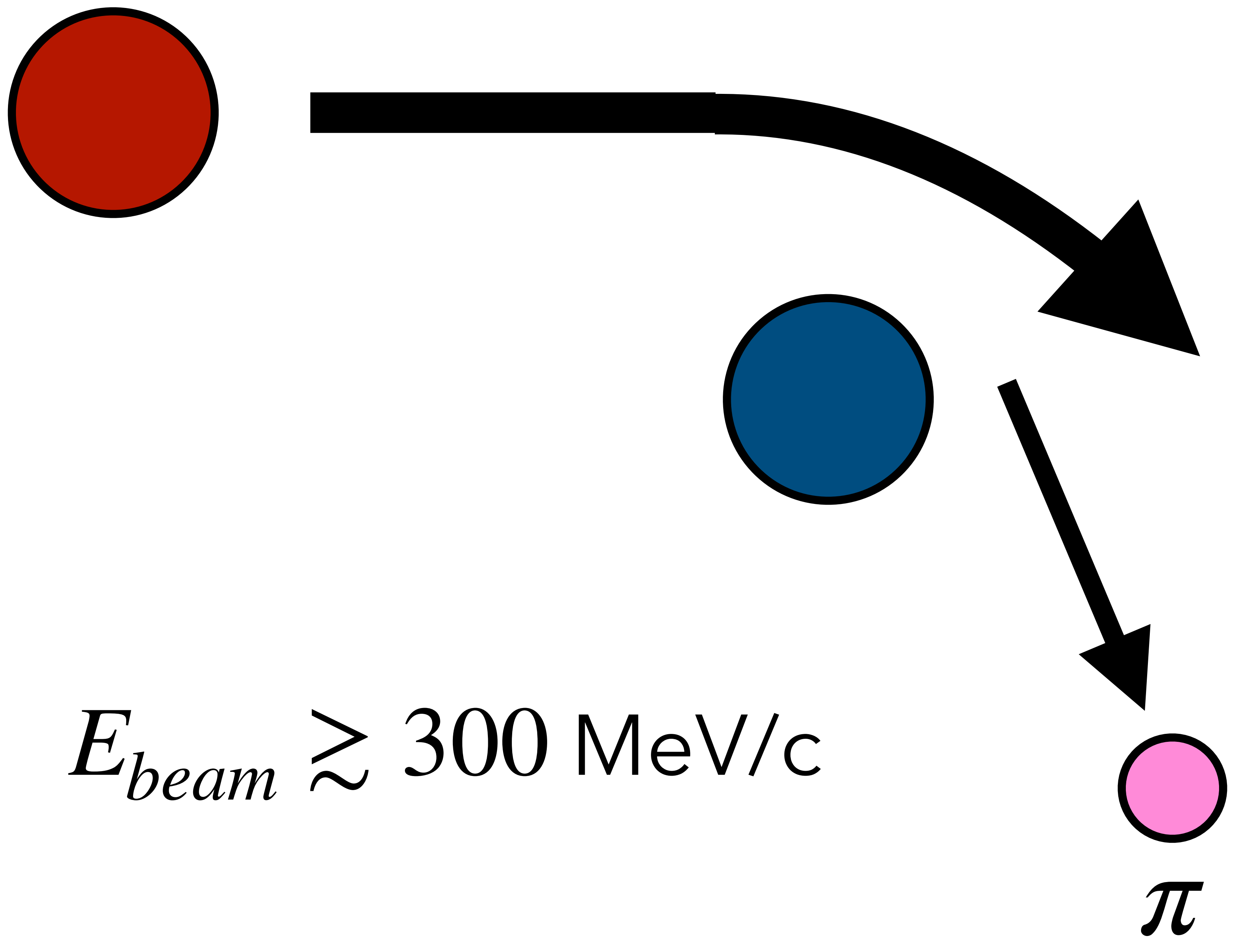

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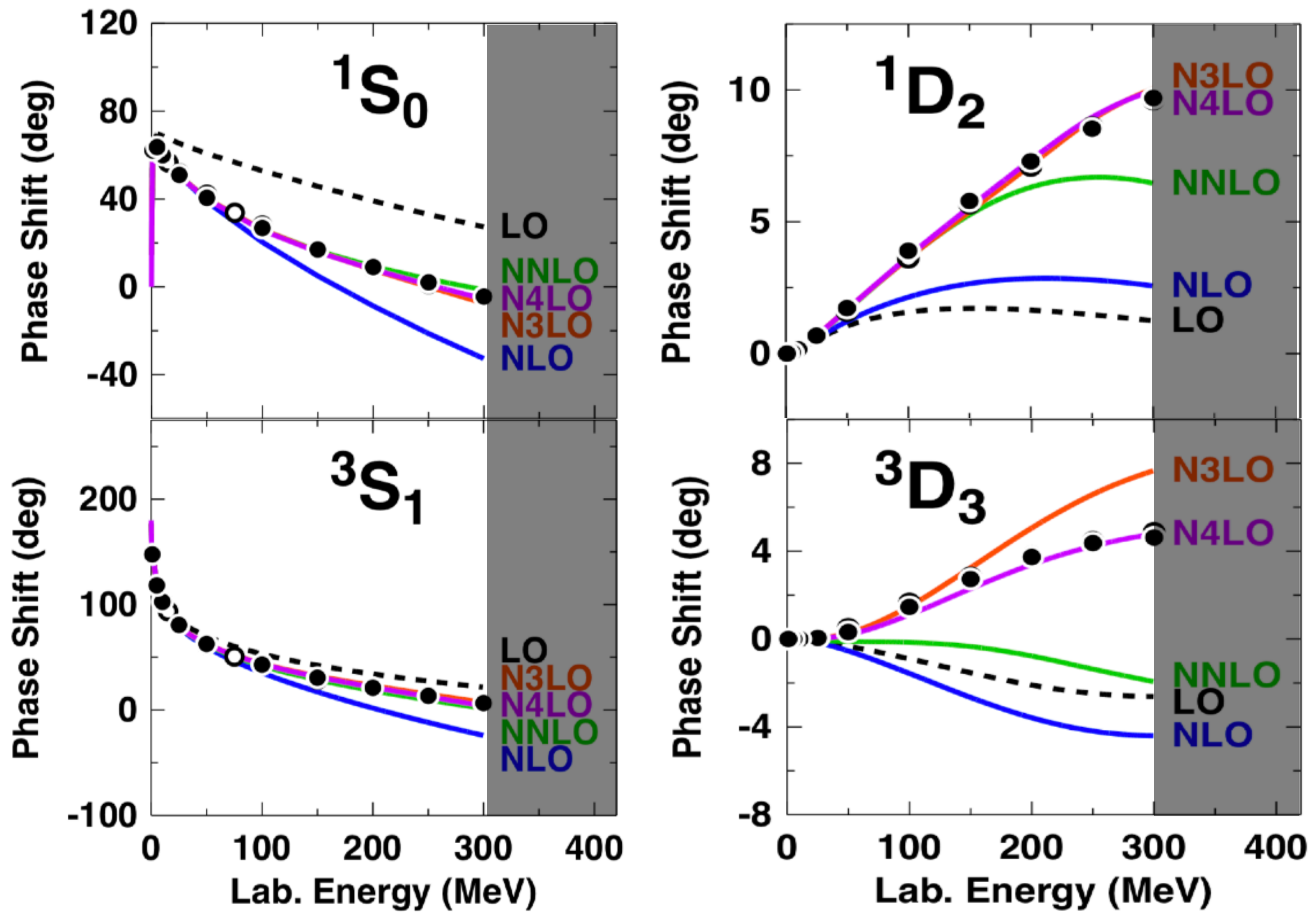

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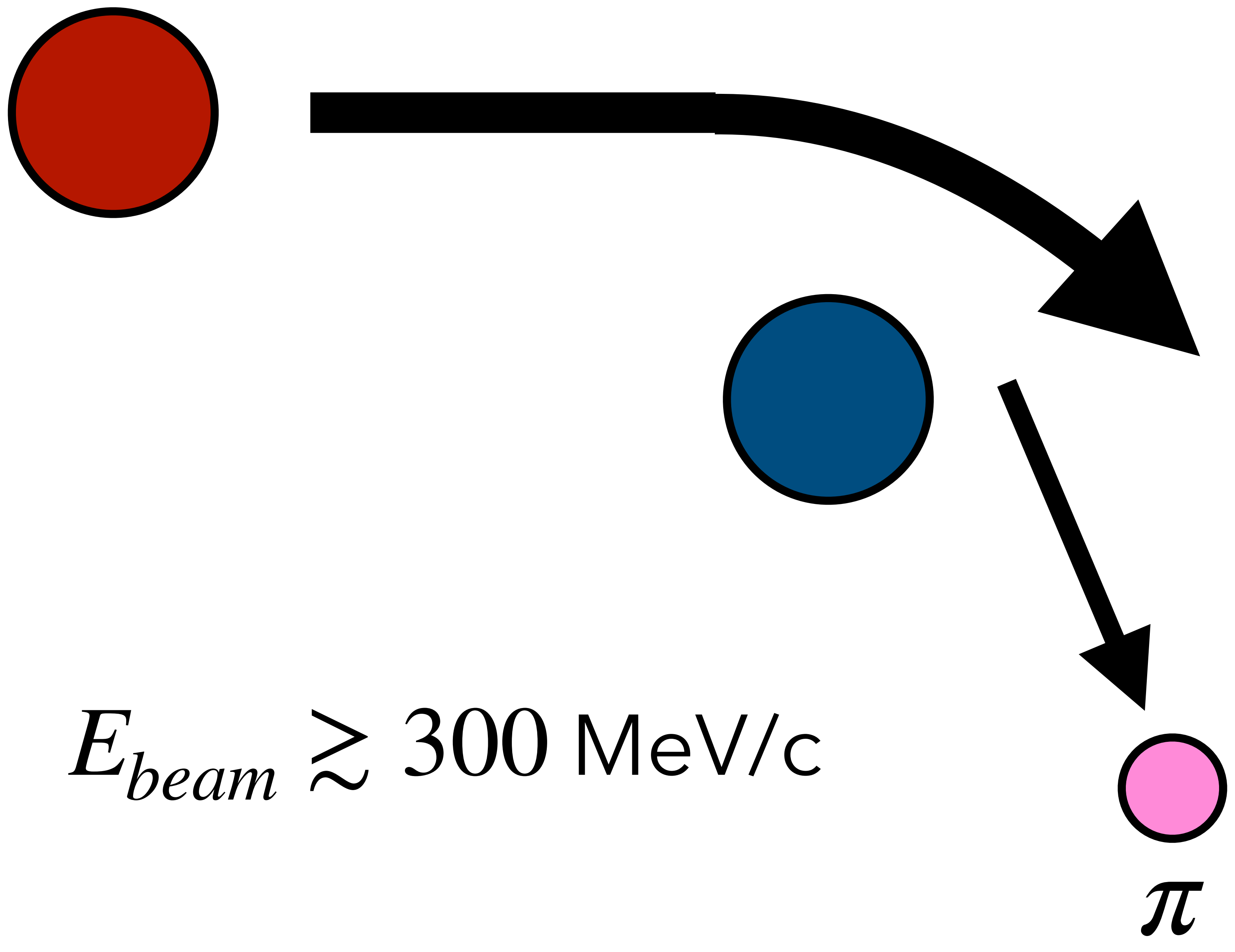

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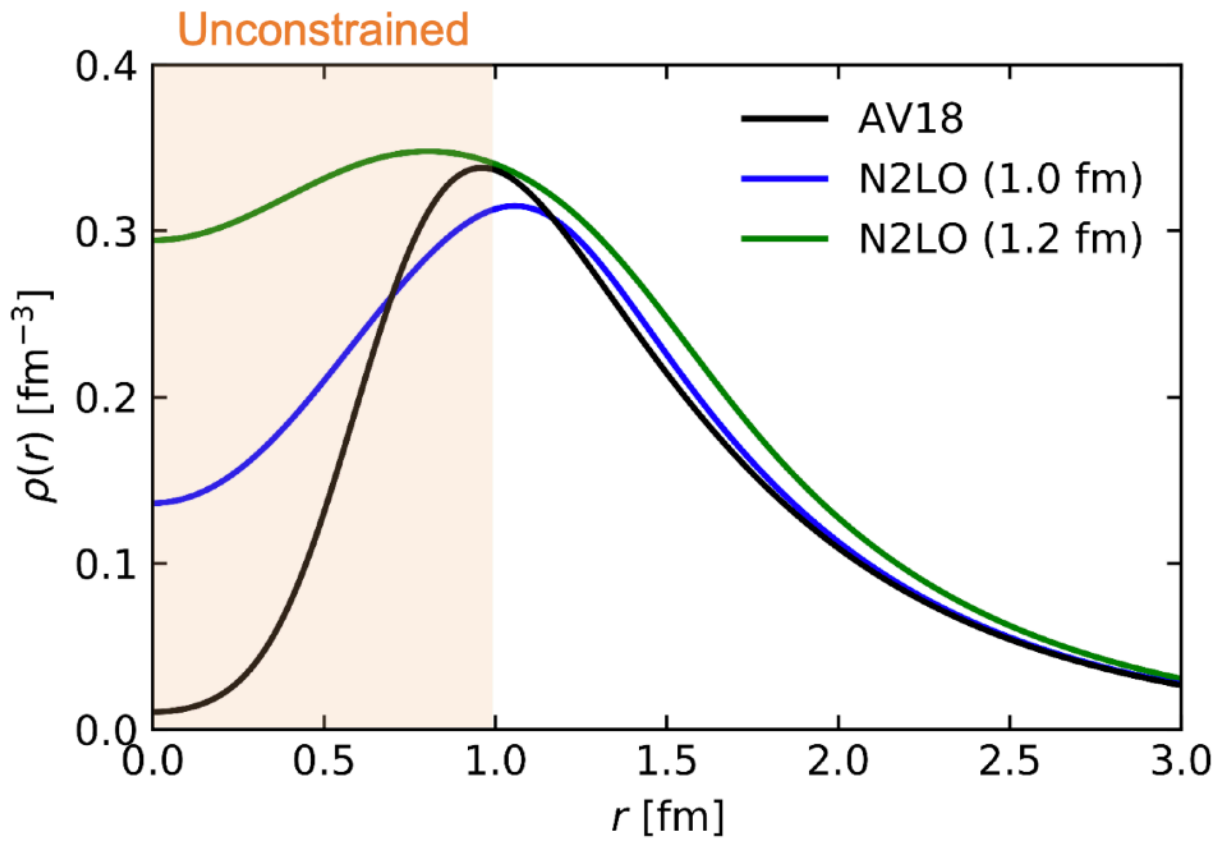

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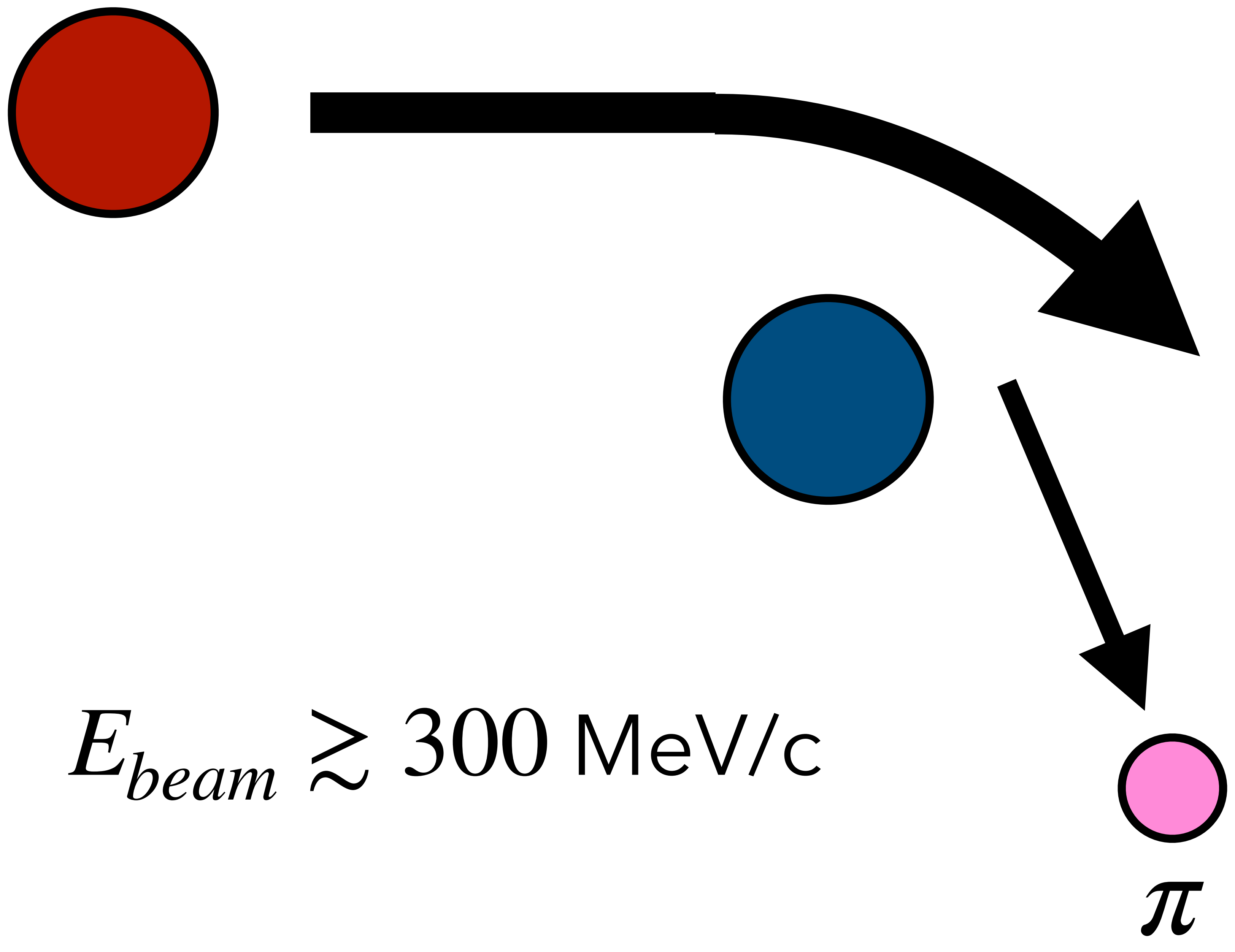

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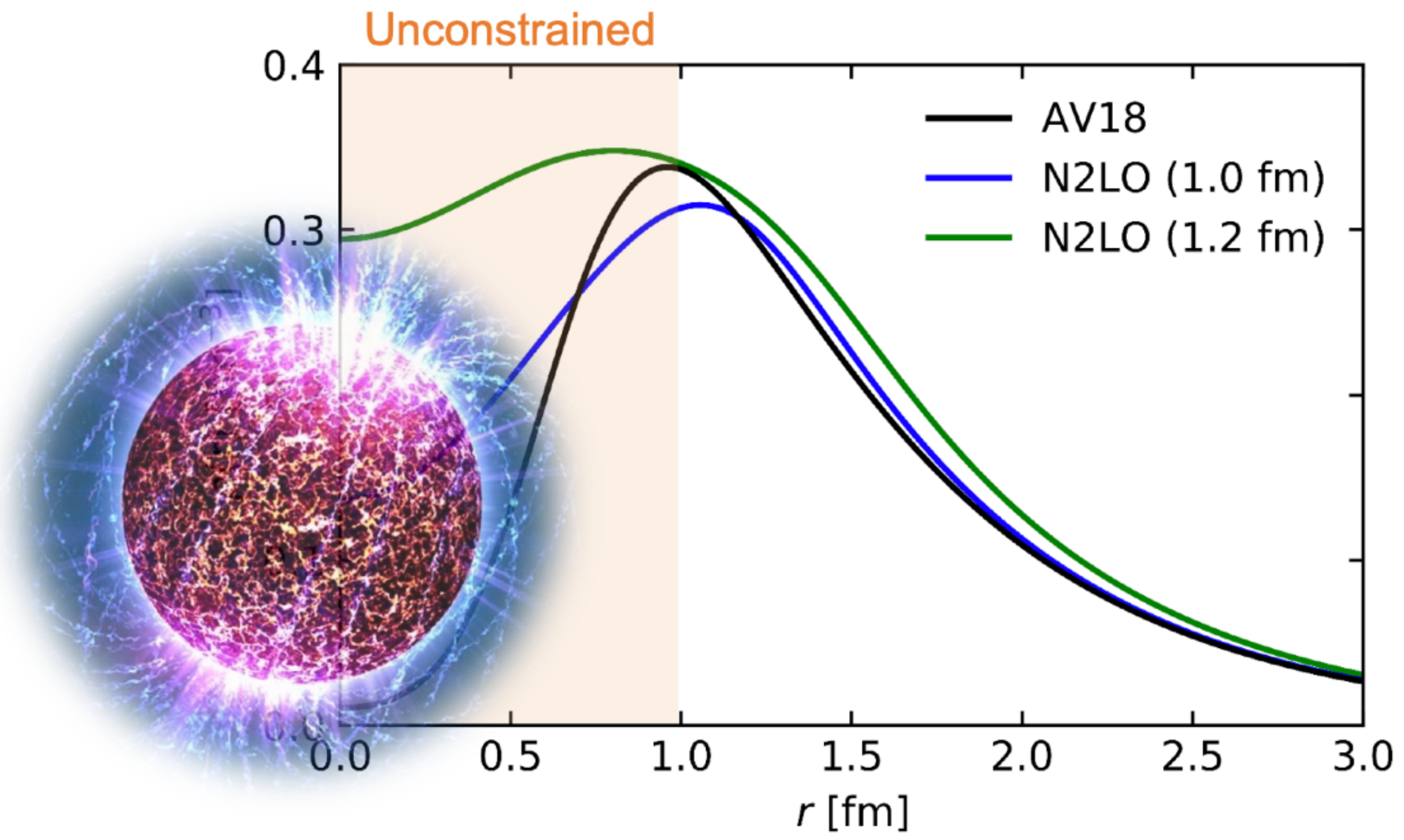
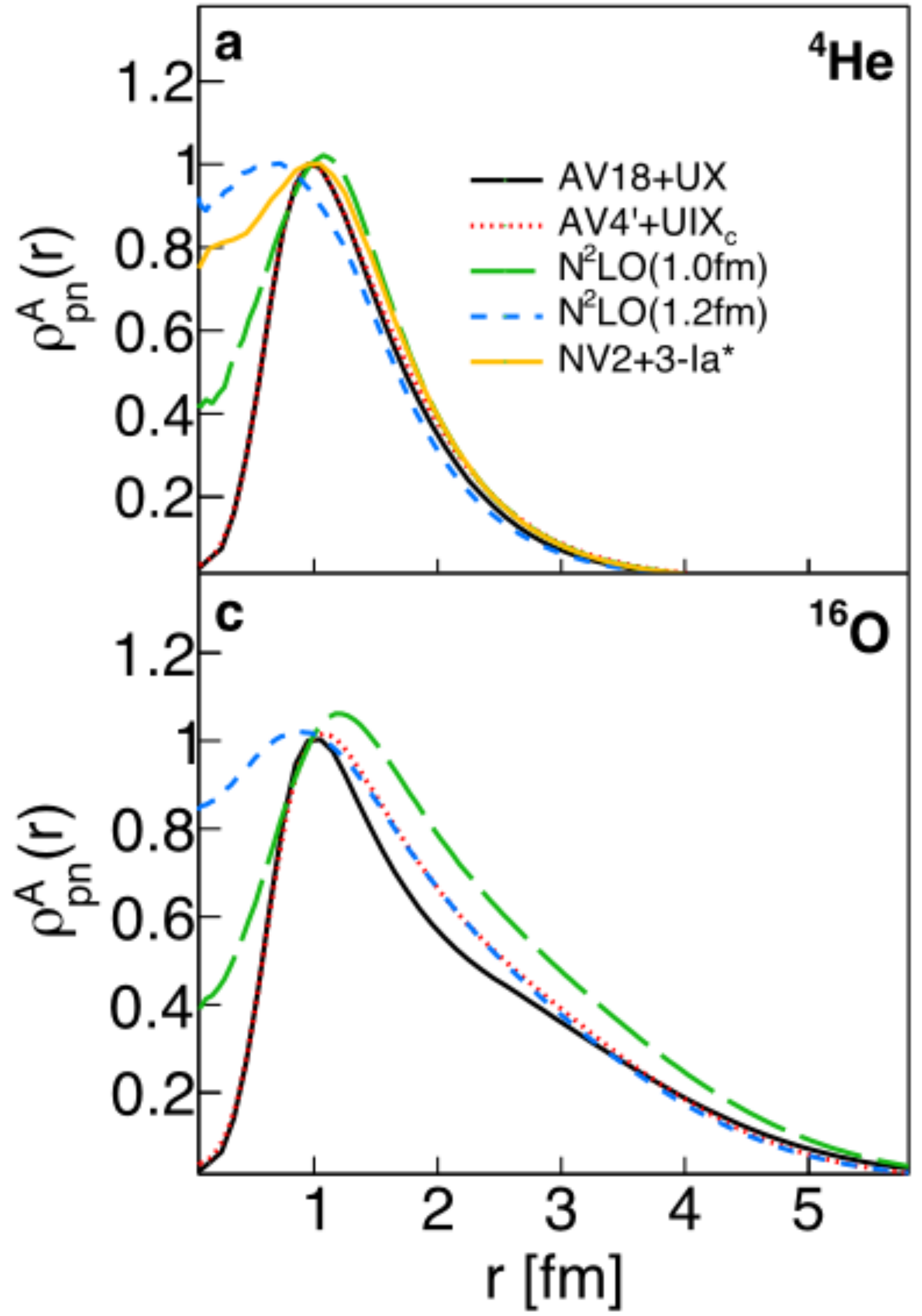
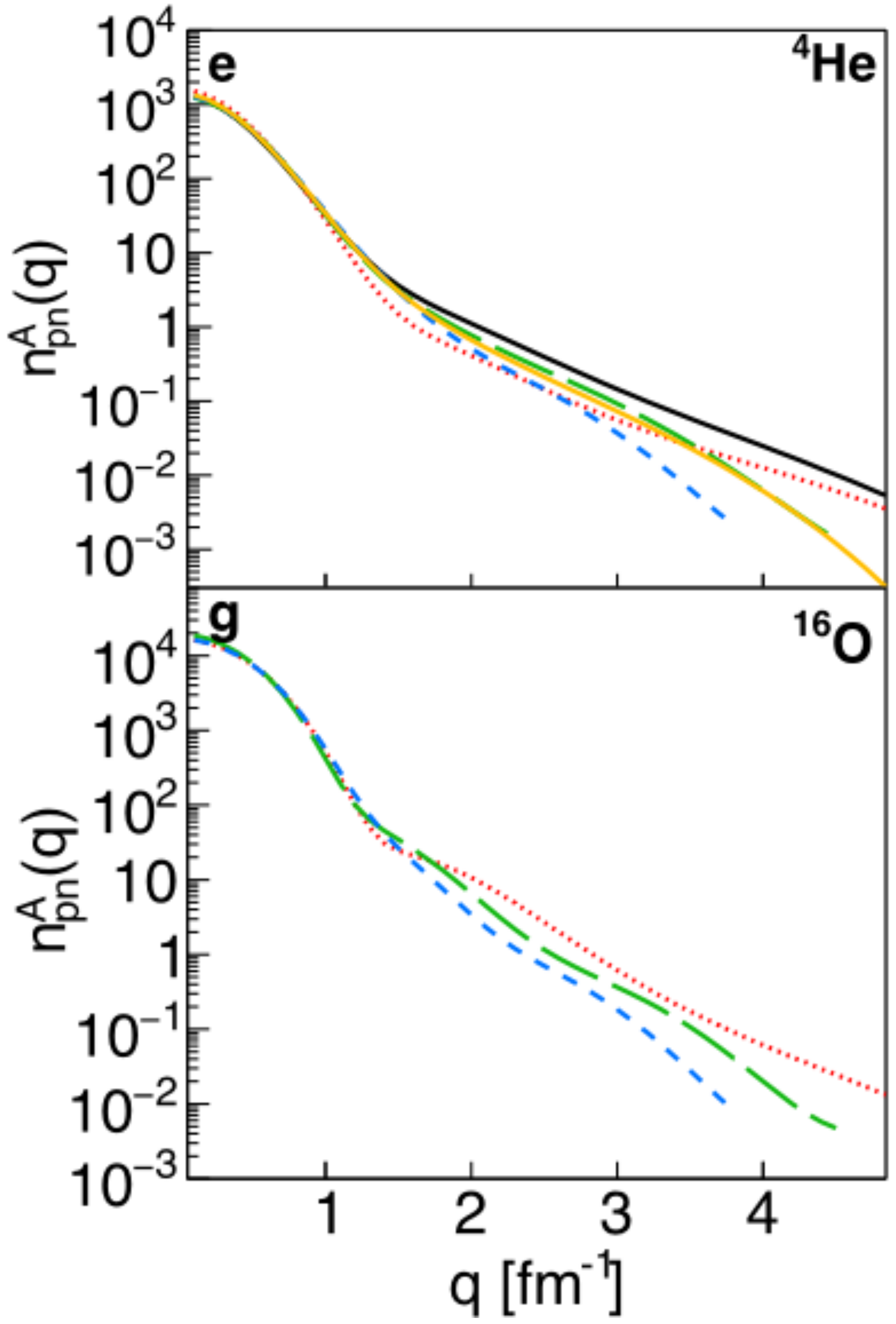
Neutron star densities!



Consequence: Large model-dependence in nuclear structure calculations

Relative **distance** for neutron-proton pairs

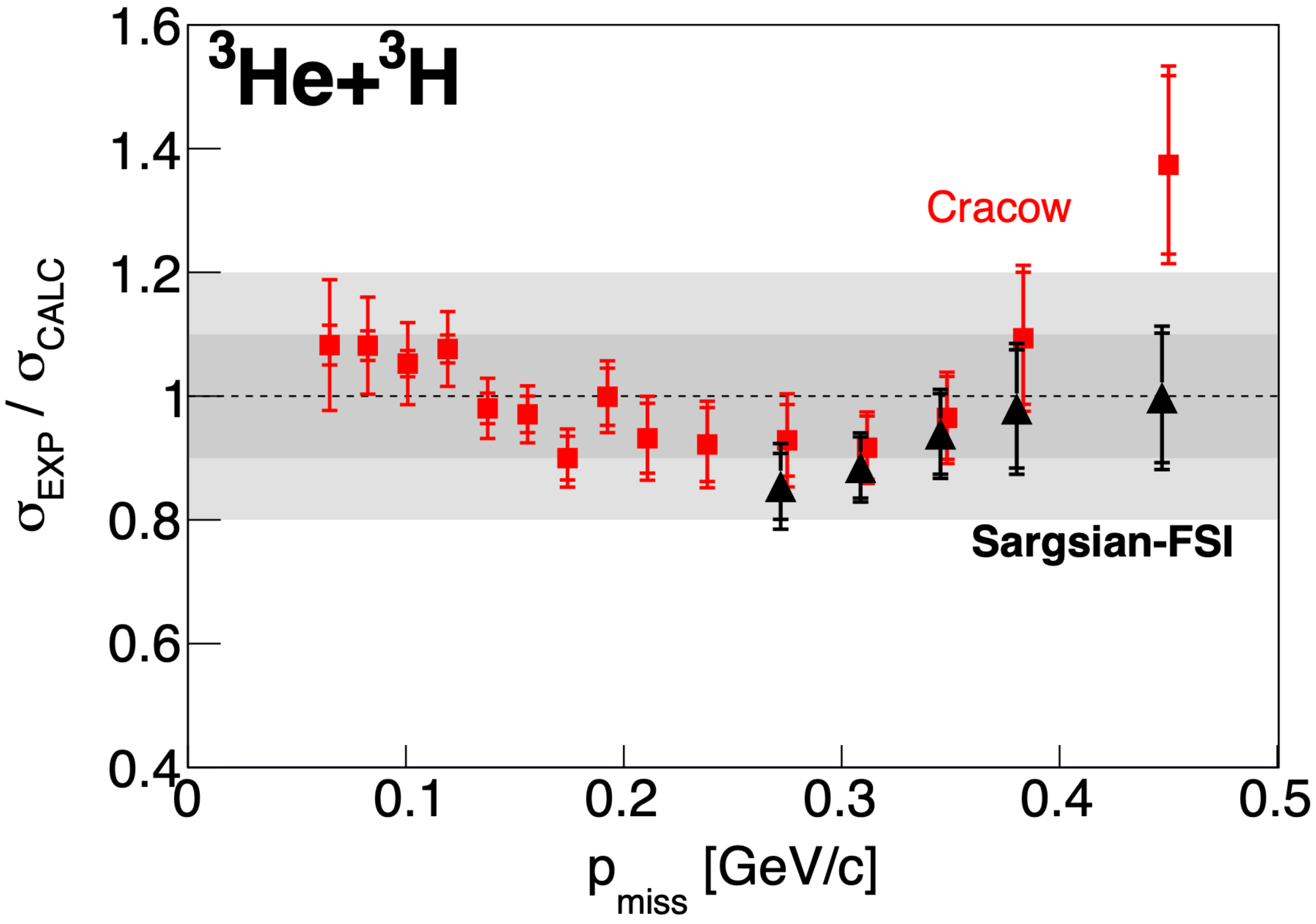


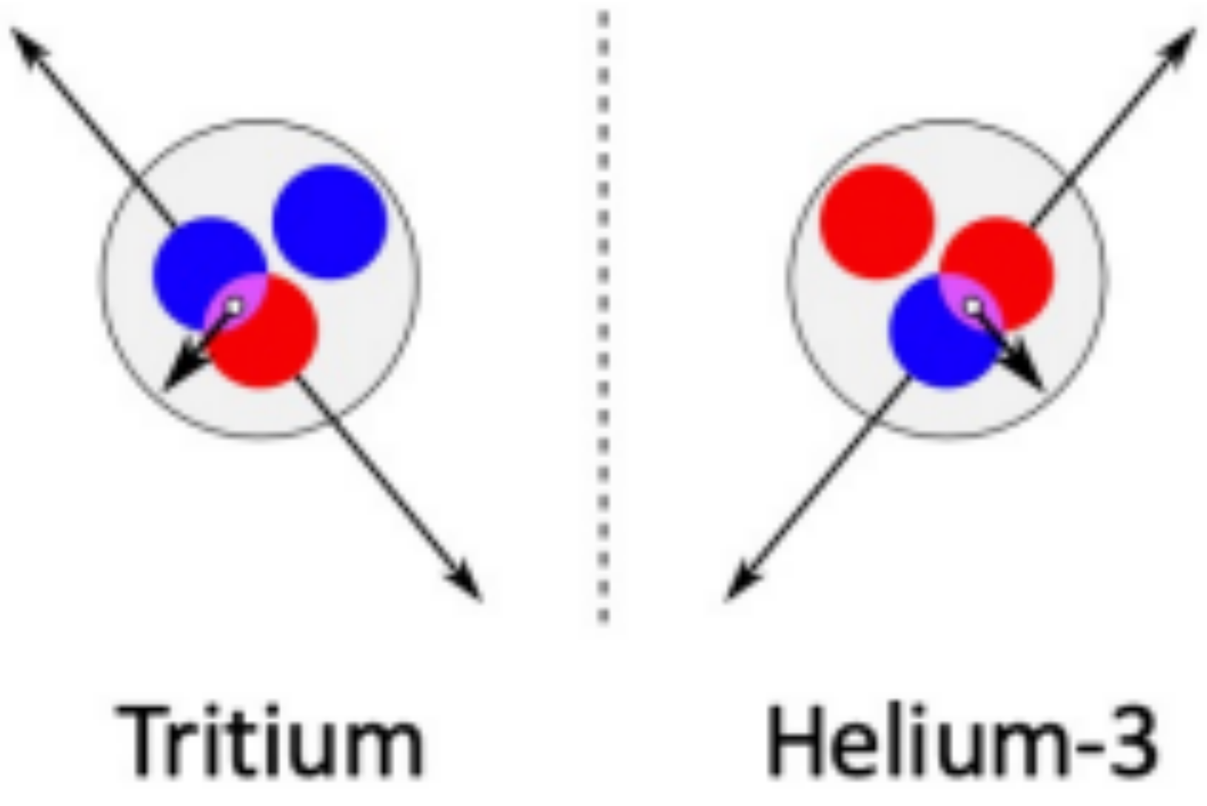


Relative **momentum** for neutron-proton pairs

Cruz-Torres et al. Nature Physics (2021)

$A = 3$ system is ideal to test theory calculations





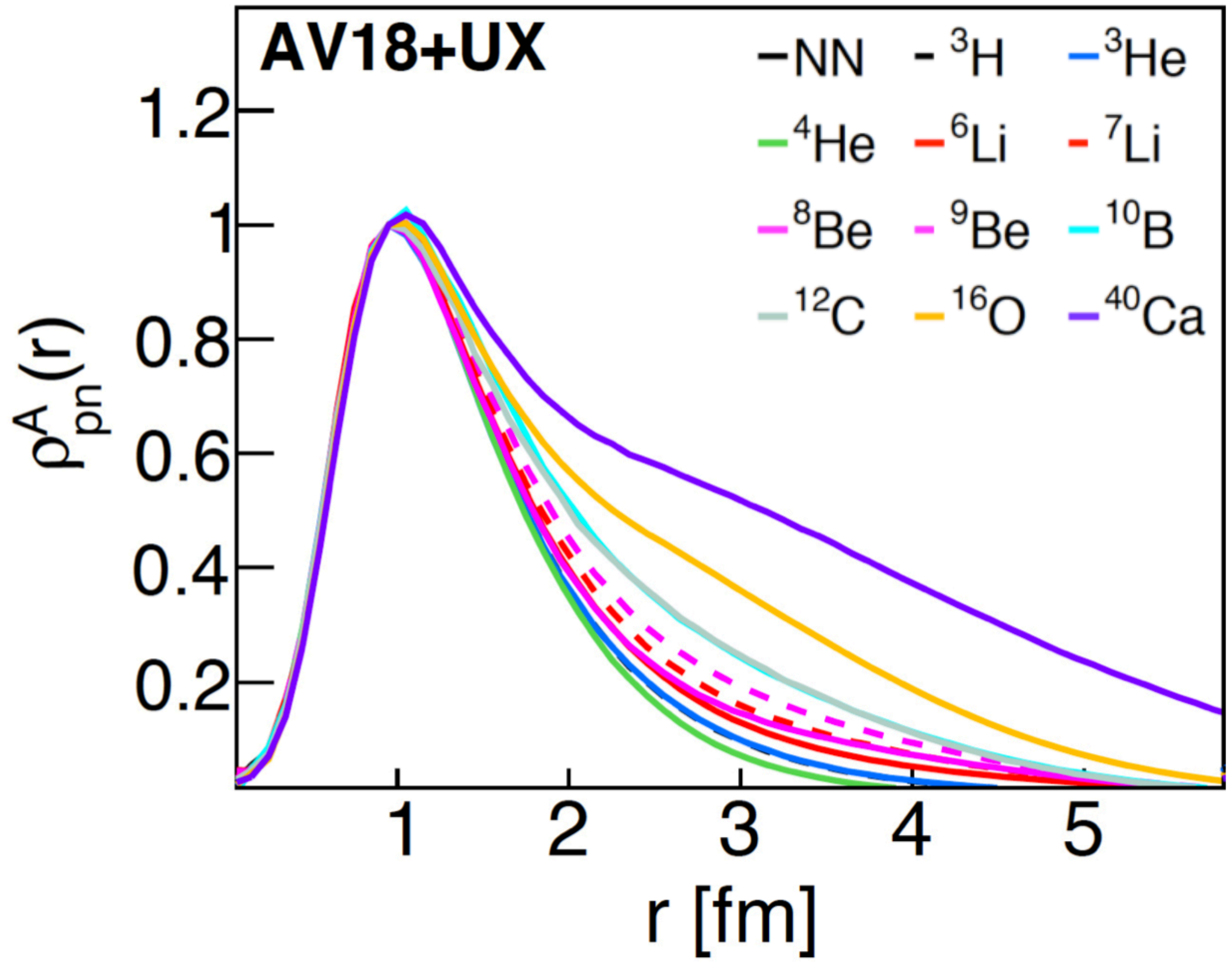
Light $A = 3$ systems allow *exact* "spectral function" and final-state rescattering calculations

Current theory can describe data up to 500 MeV/c momentum!

Cruz-Torres et al. PRL (2020)
Cruz-Torres et al. PLB (2019)

But what if we look at one model?

Short-distance nuclear structure scales across nuclei!



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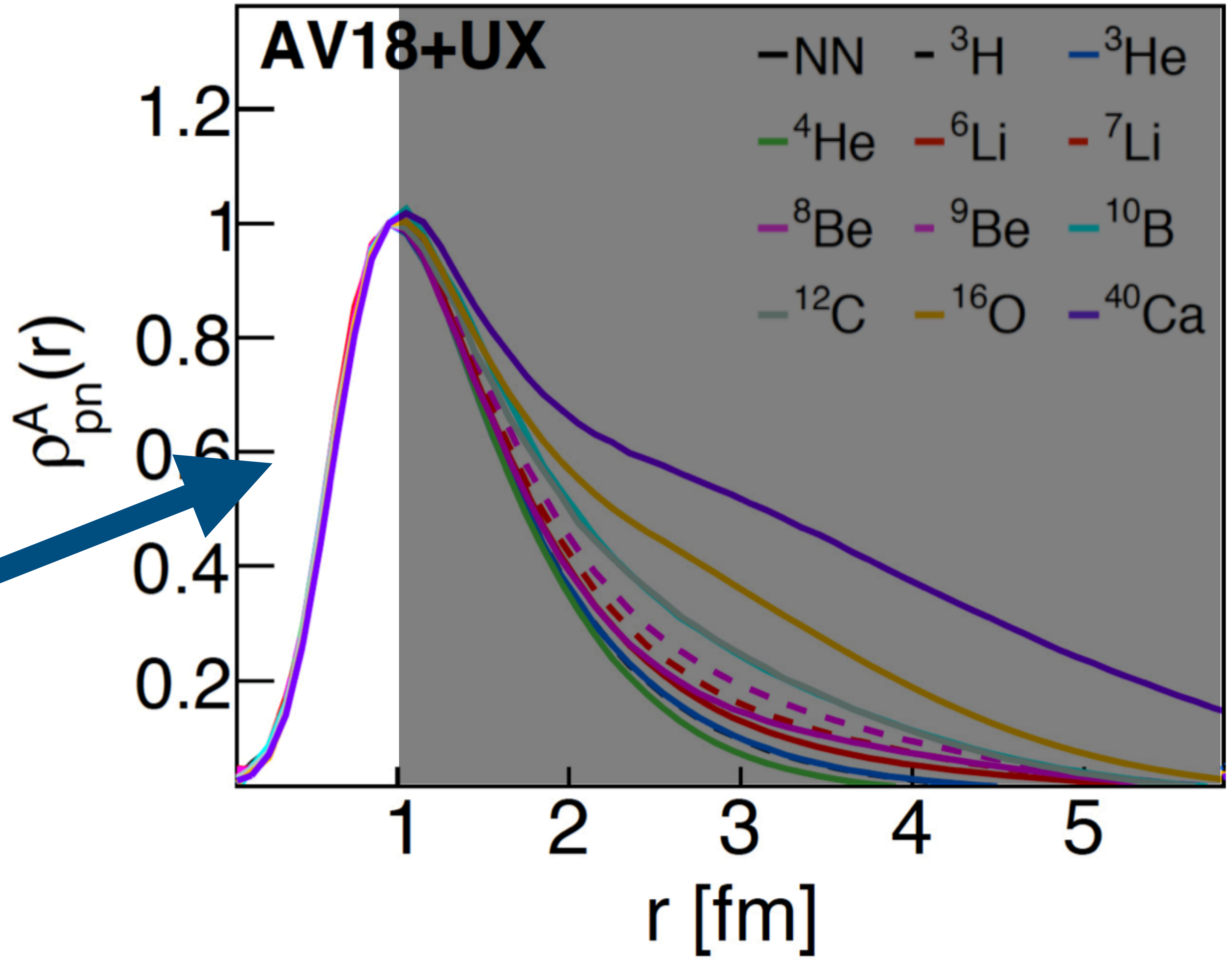

Factorization!

Many Body = Constant × Two Body

Cruz-Torres et al. Nature Physics (2021)

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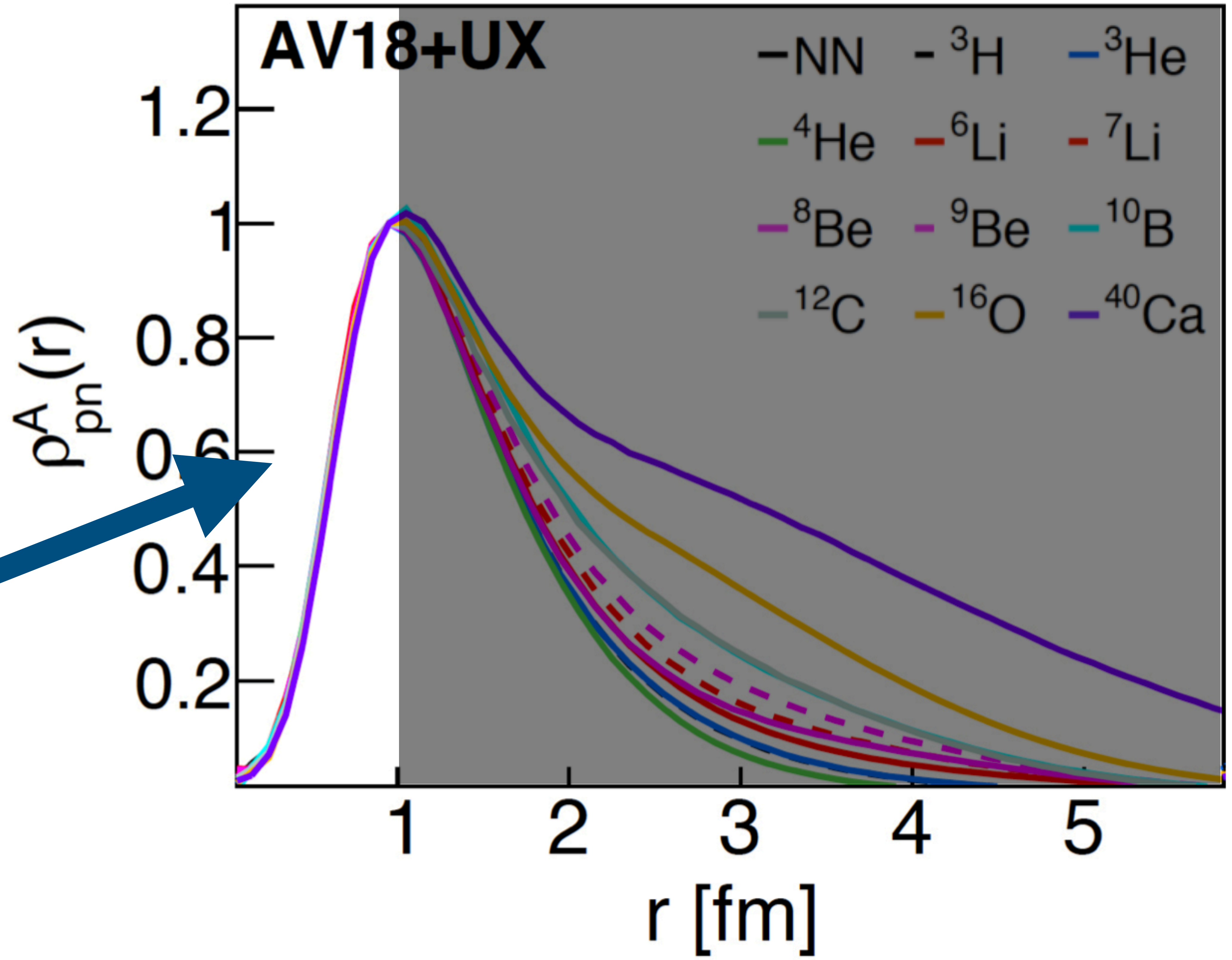
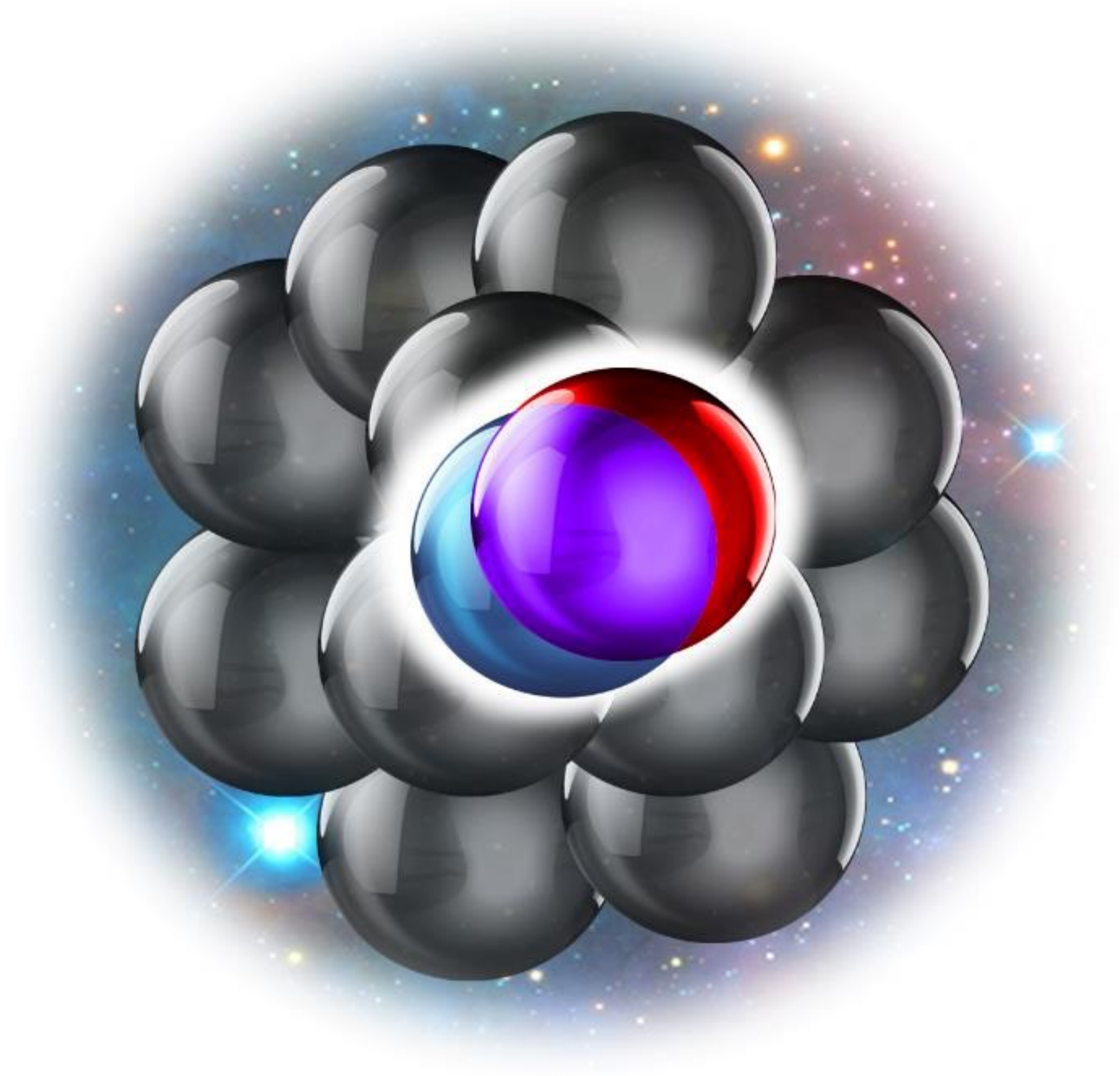


Factorization!

Many Body = Constant × Two Body

$$\rho_A^{NN,\alpha}(r) = C_A^{NN,\alpha} \times |\phi_{NN}^{\alpha}(r)|^2$$

Separation of Scales

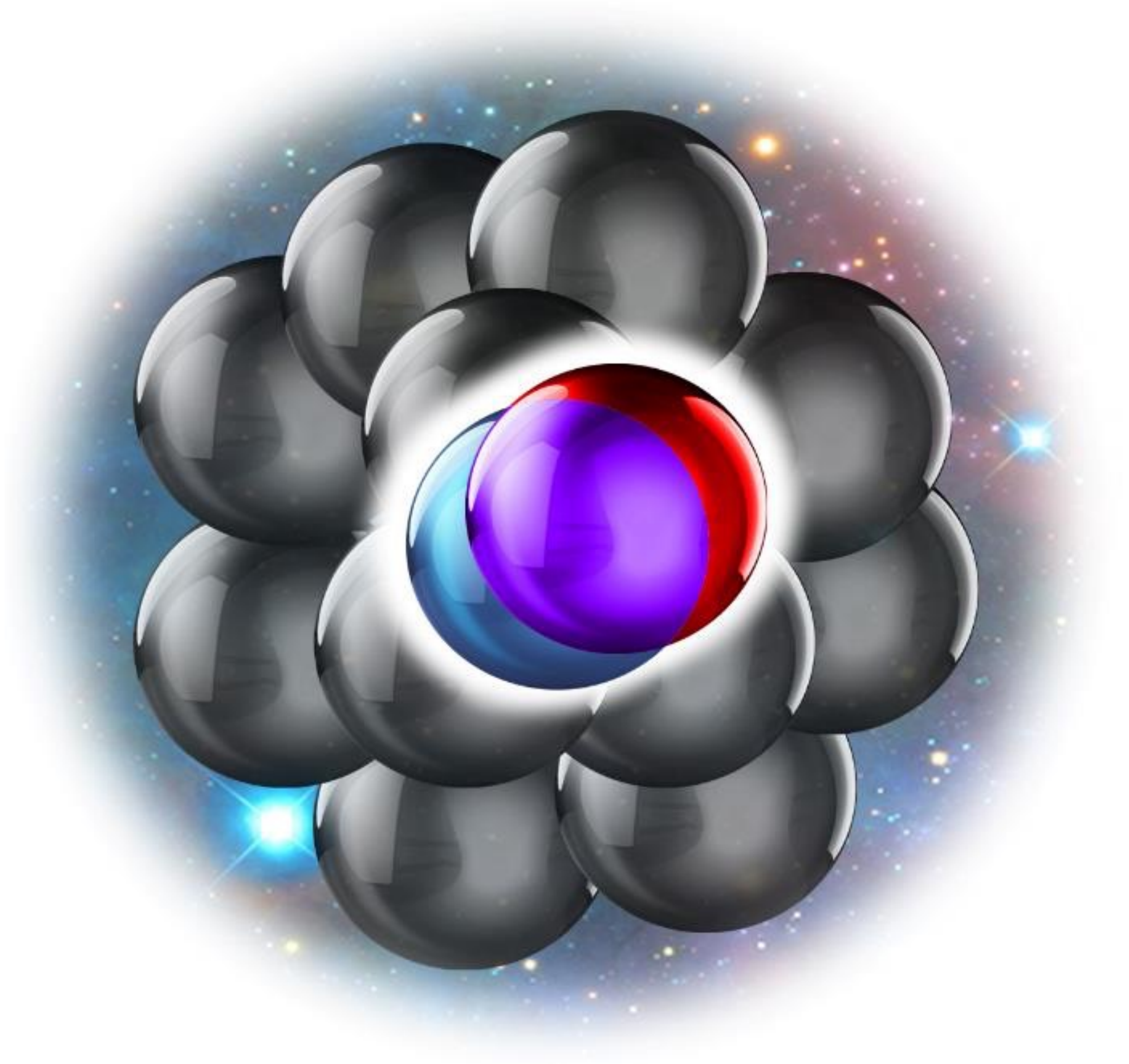


$$r_{rel} \ll R_A$$

$$k_{rel} \gg k_F$$

- Distance and momentum scales are much different inside pairs than the rest of the nucleus!

Separation of Scales



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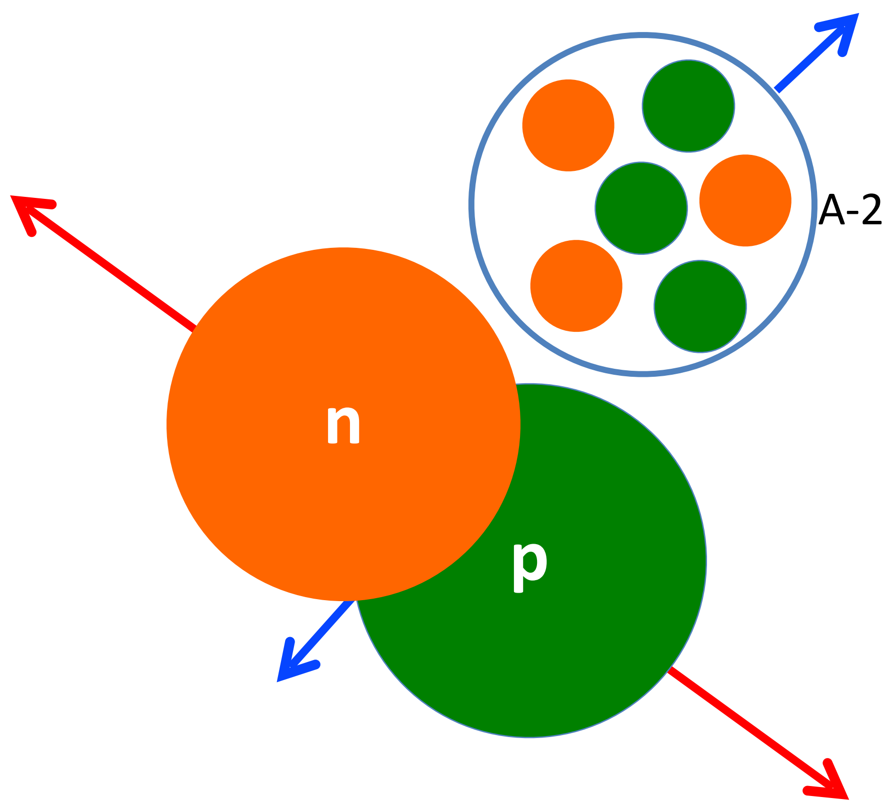
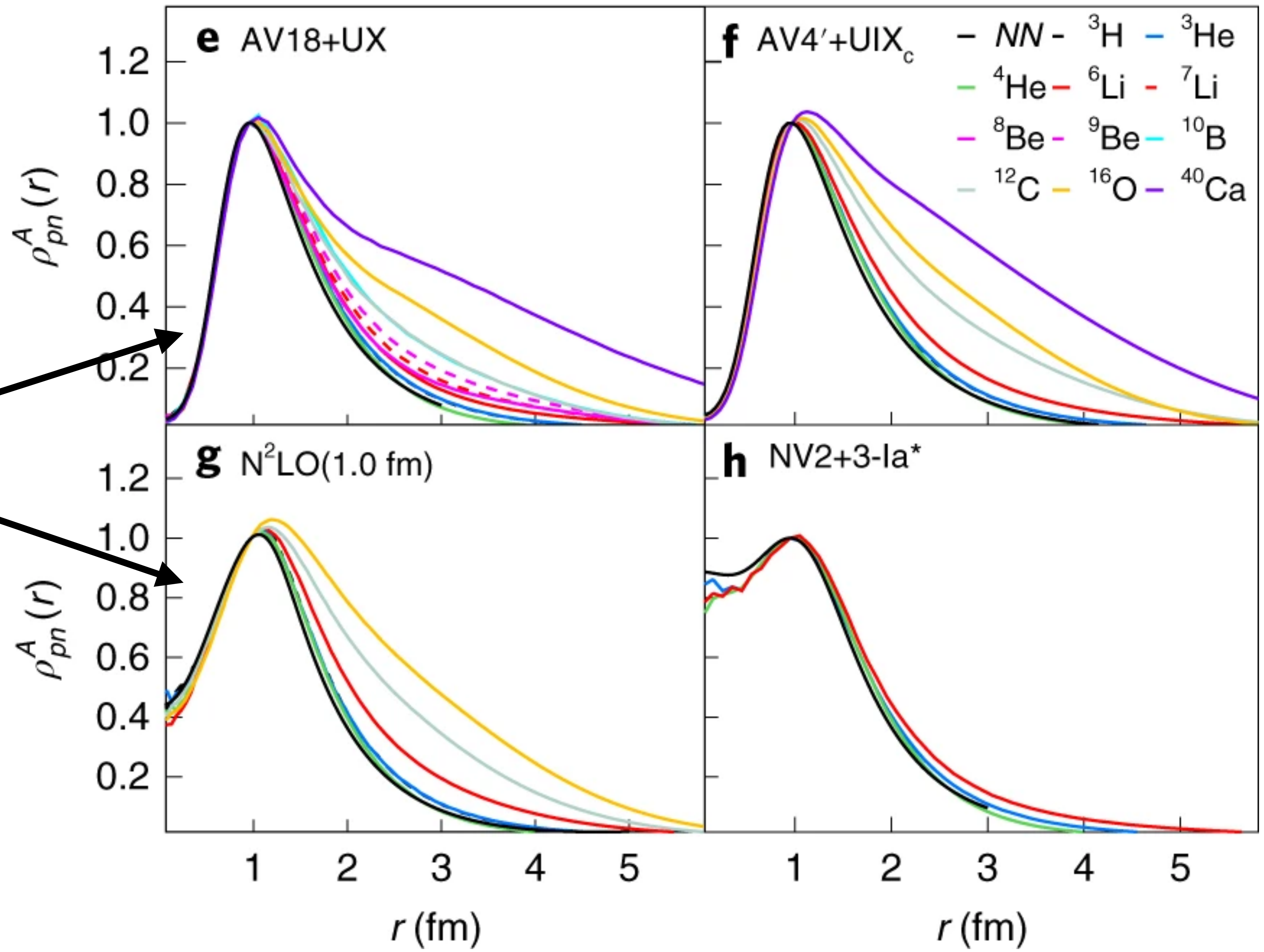


- Distance and momentum scales are much different inside pairs than the rest of the nucleus!
- Strong in-pair interactions **decouple** from the rest of the nucleus

➡ **Universal** behavior of SRC pairs across nuclei

Factorization is *Scheme* Independent

Different models give different short-distance behavior, but **always** universal!



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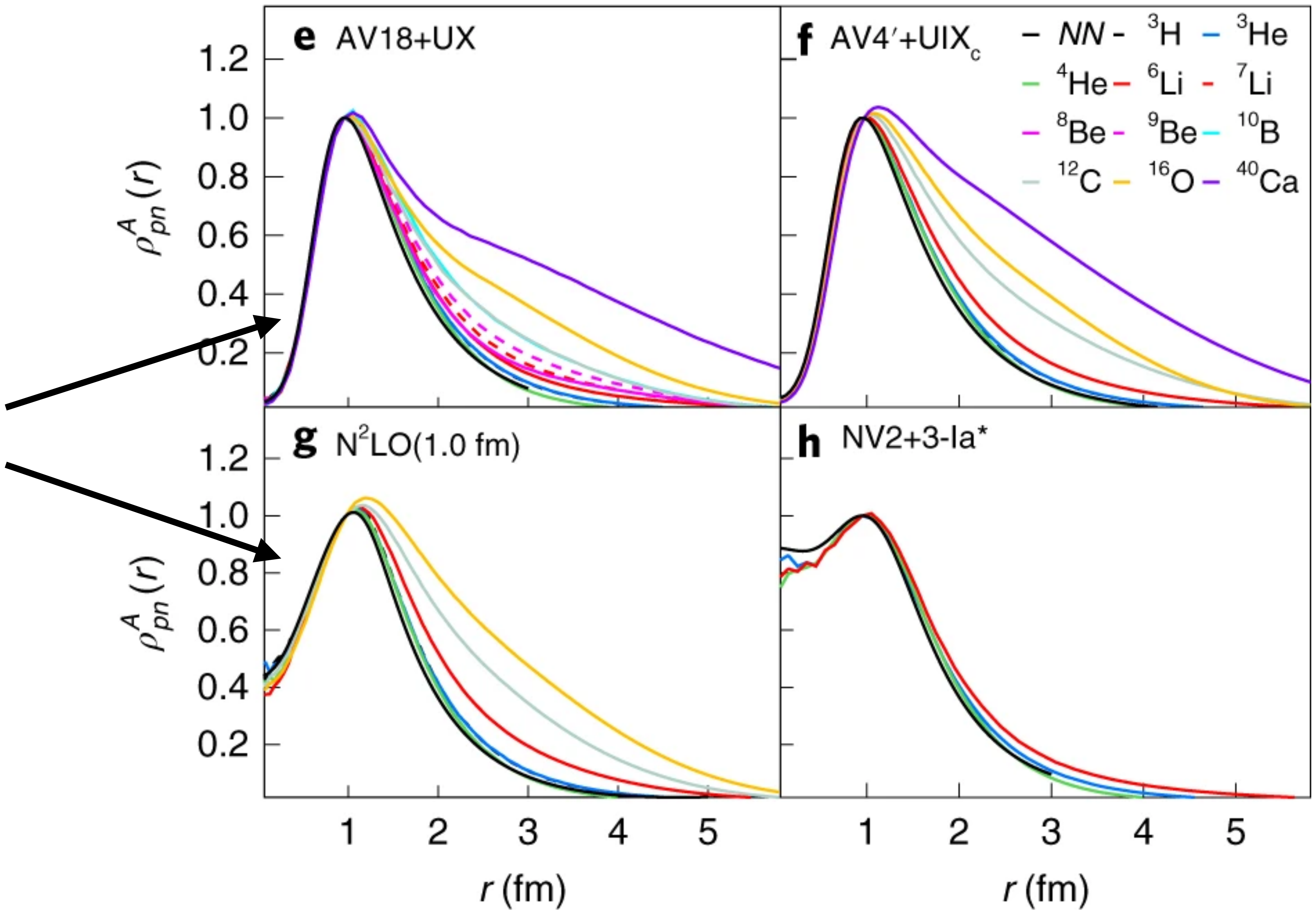
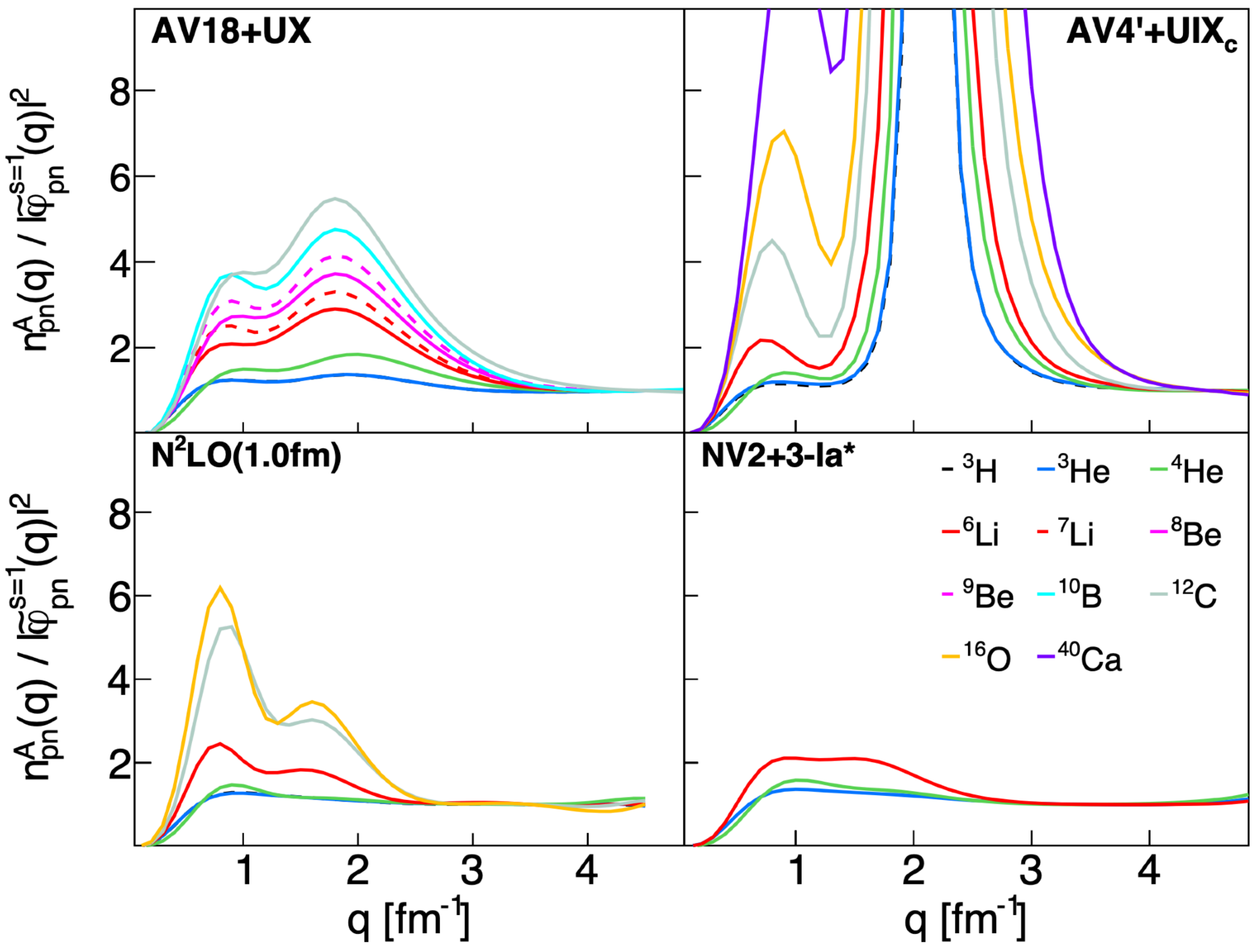
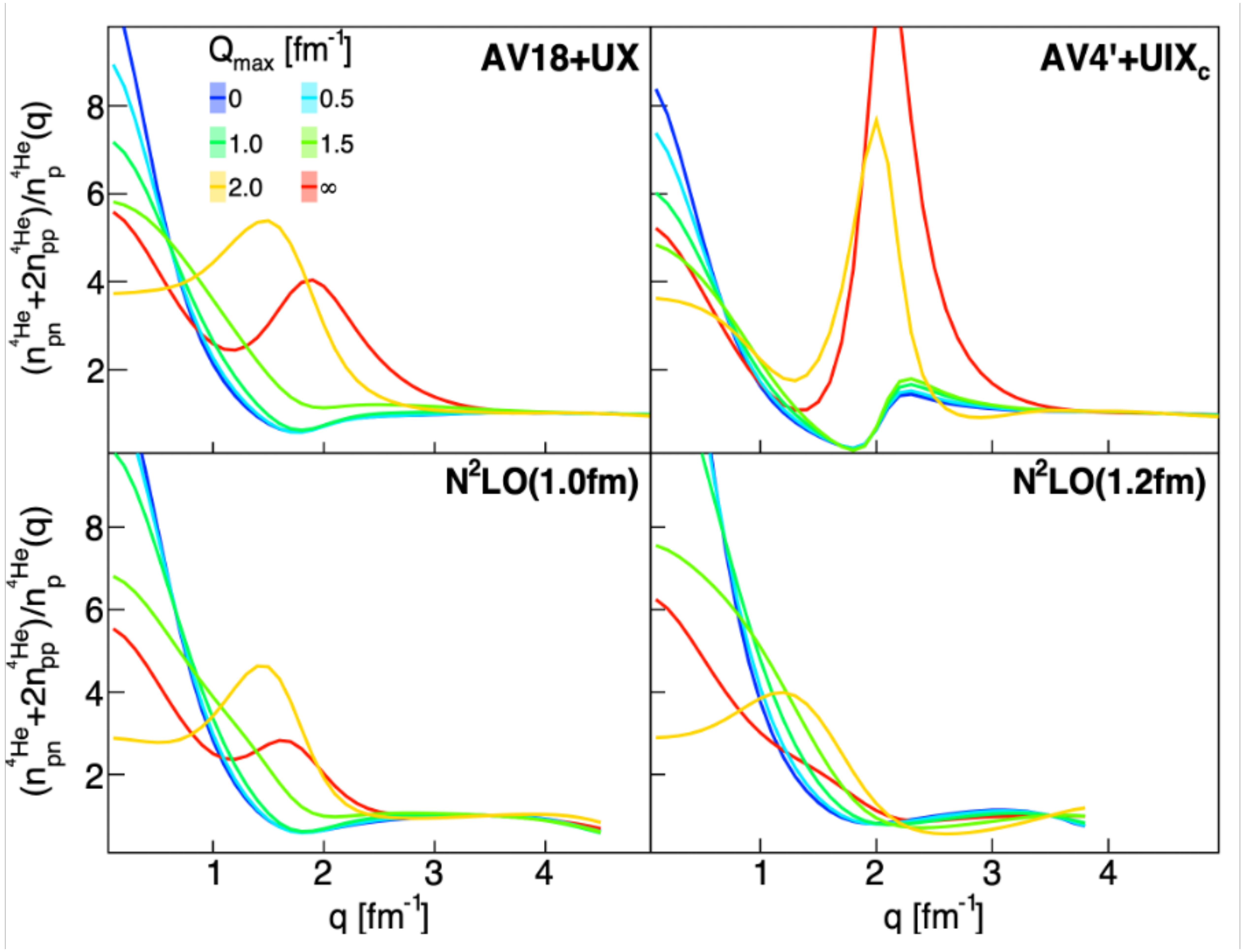


Factorization also works in *momentum*



Cruz-Torres et al. Nature Physics (2021)

Momentum-scaling onset depends on Q_{CM}



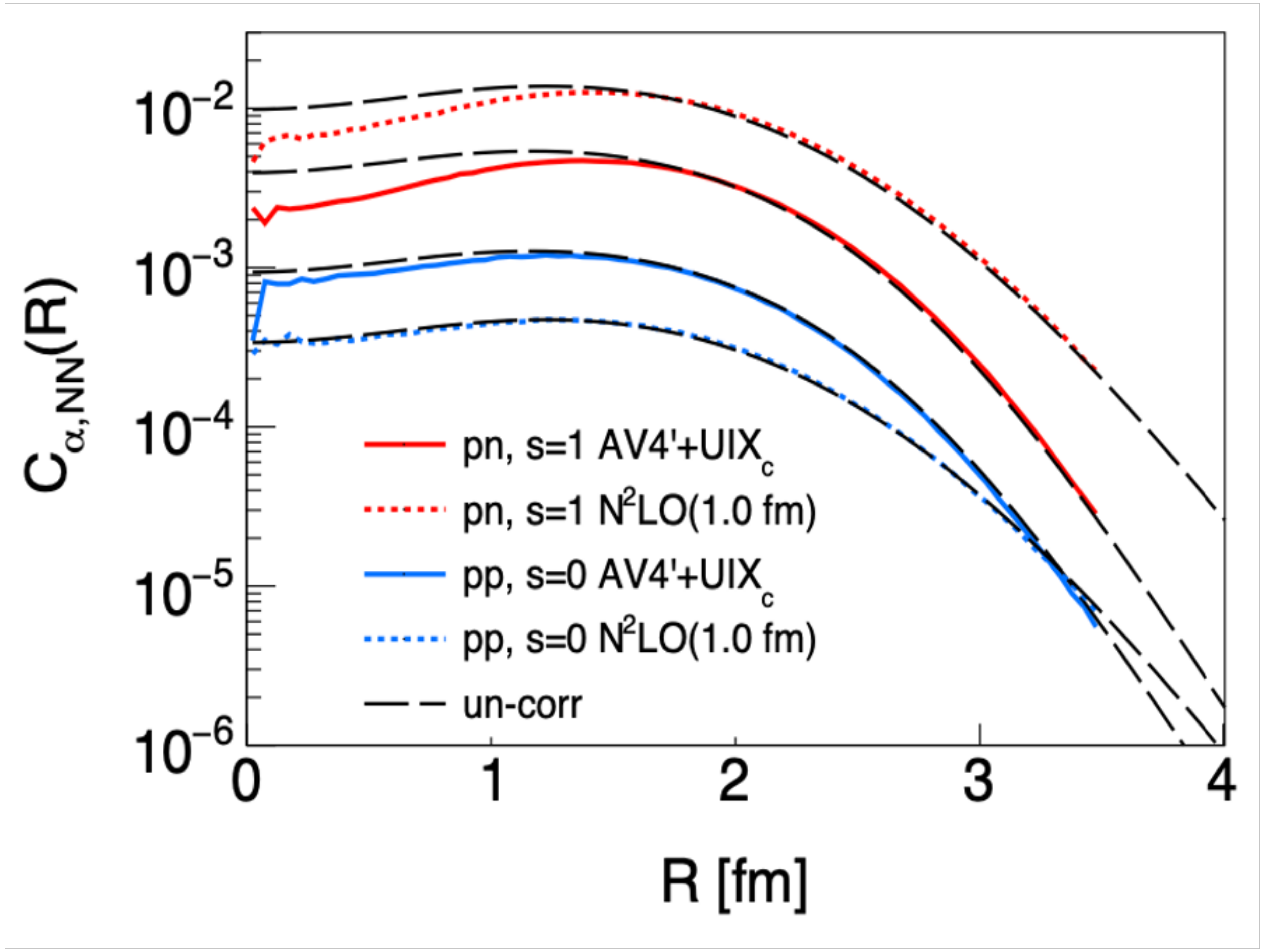
Cruz-Torres et al. Nature Physics (2021)

SRC Pair Densities

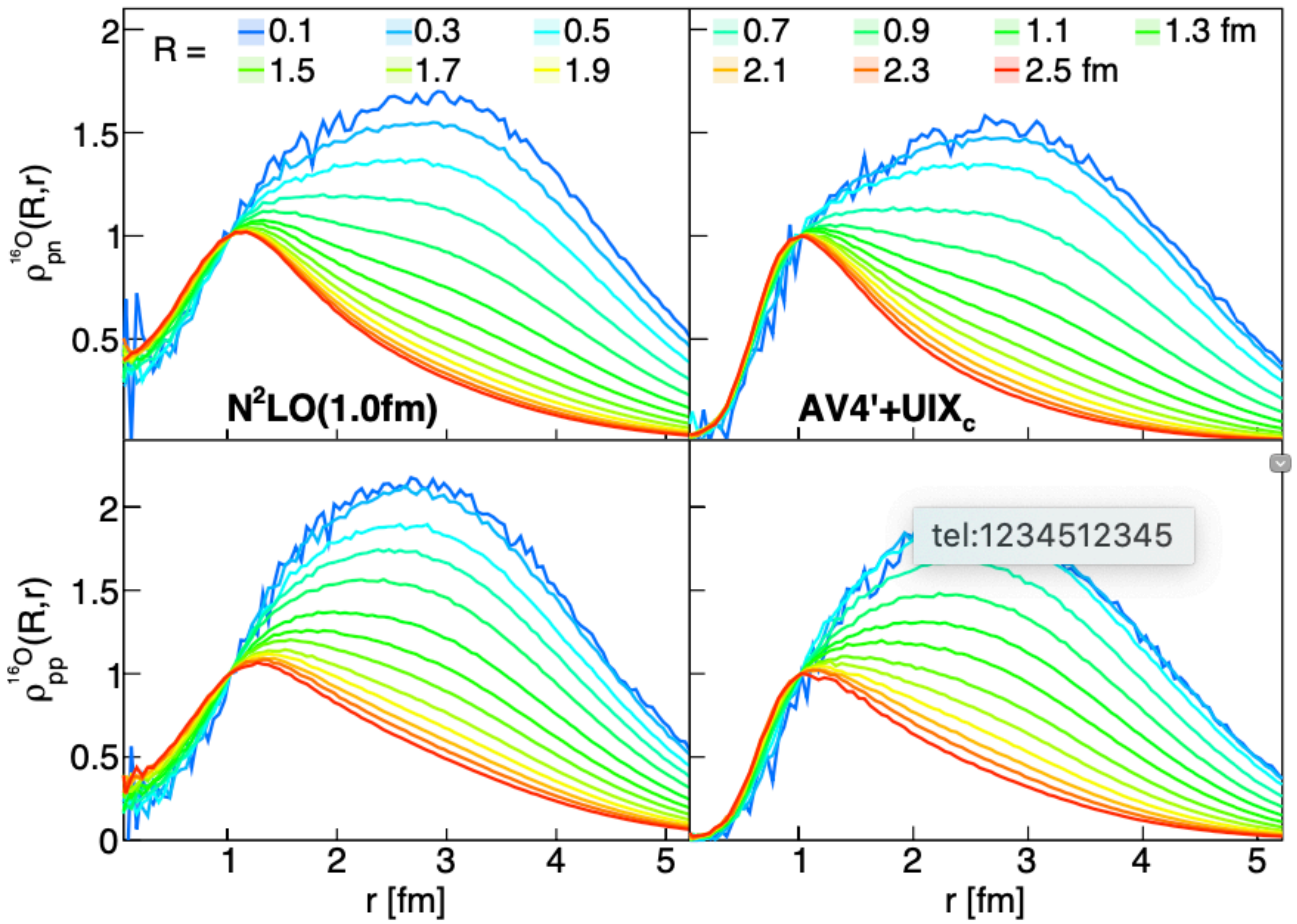
$$\rho^A_{NN}(r,R) = C^A_{NN}(R) \times \left|\varphi_{NN}(r)\right|^2$$

$$\Rightarrow C^A_{NN}(R) = \int_0^{1\,fm} d\Omega_R d\mathbf{r}\ \ \rho^A_{NN}(r,R) \,/\, \left|\varphi_{NN}(r)\right|^2$$

SRC pair densities are largely a function of the mean-field

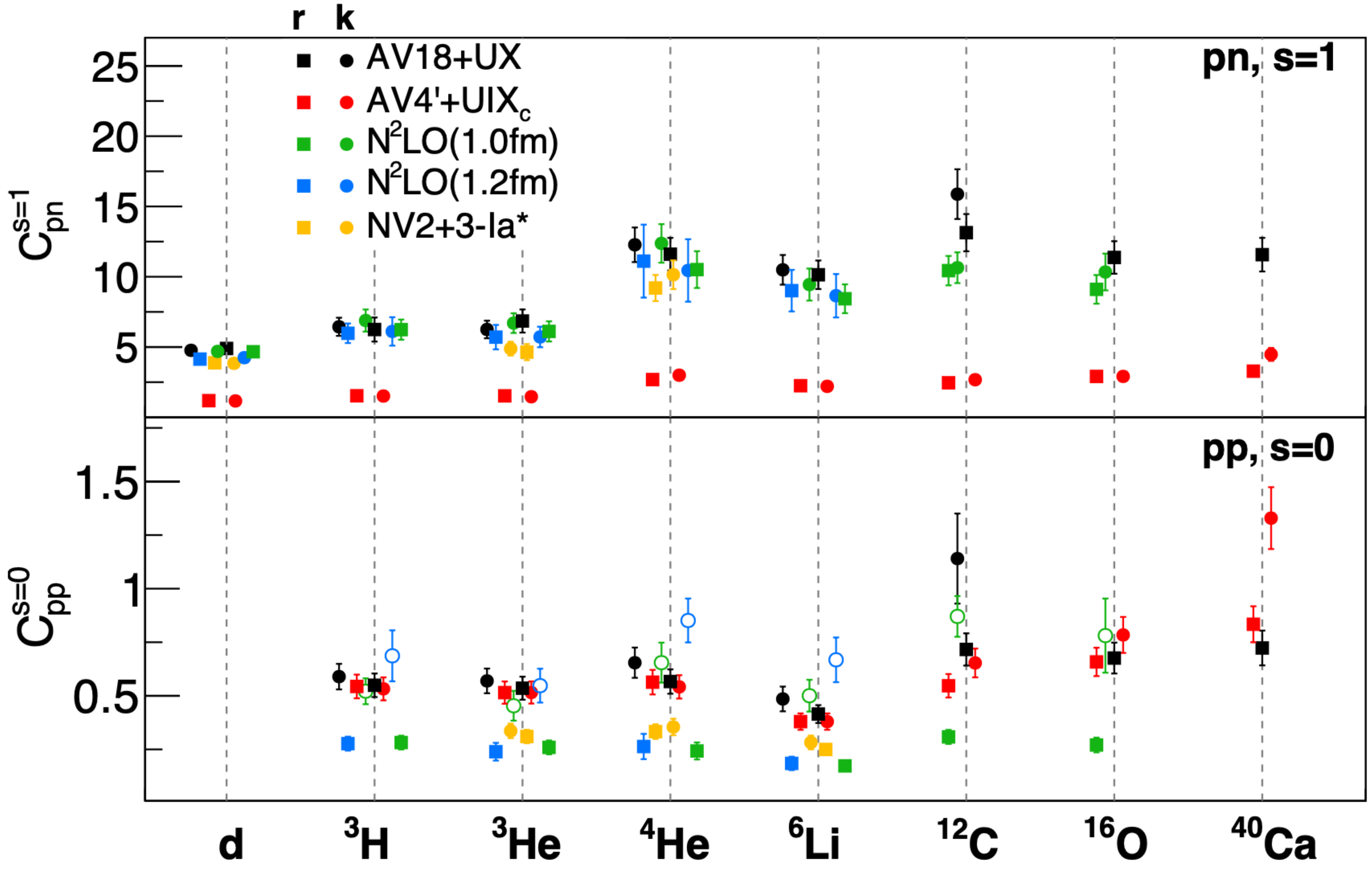


Factorization is *position* independent



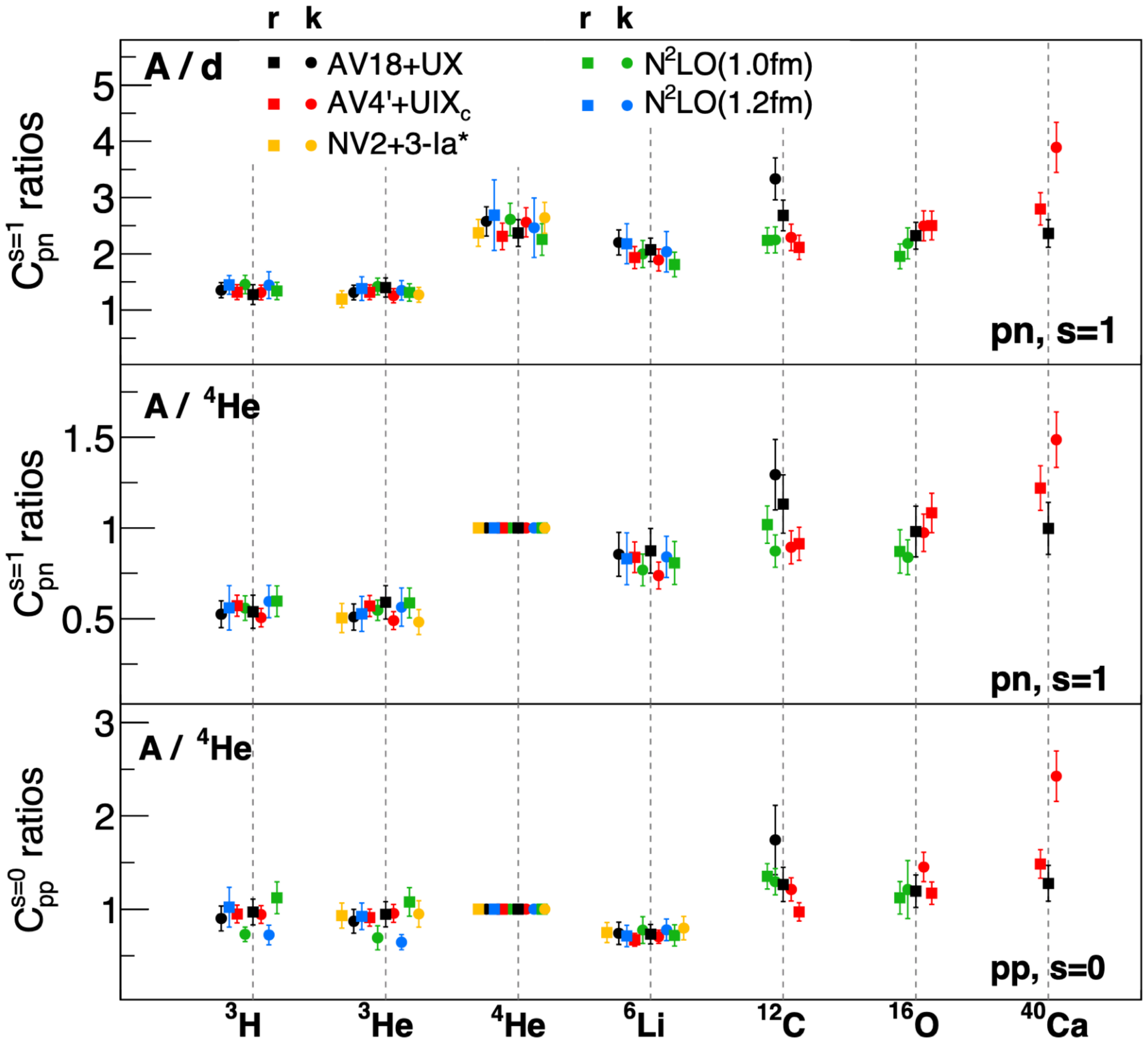
Cruz-Torres et al. Nature Physics (2021)

Scaling gives us SRC pair abundances



Cruz-Torres et al. Nature Physics (2021)

When cancelling 2-body effects – **universal!**



Normalizing to one nucleus to cancel different NN interaction effects

Scaling of SRC pairs in nuclei is driven by **mean-field physics**

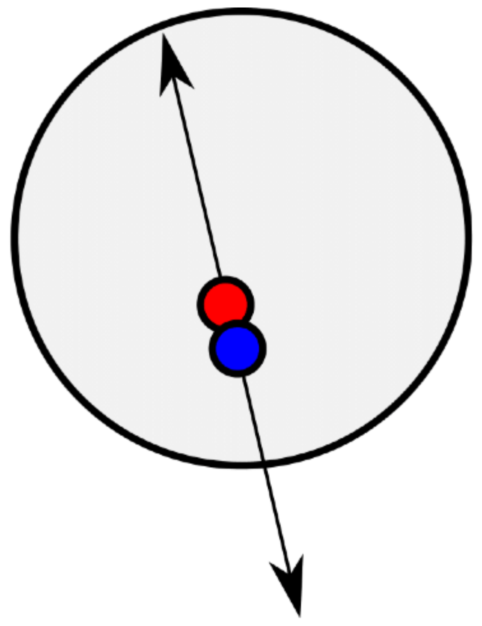
Same for all NN interactions!
Same for small-r and large-k!

Short-distance = high-momentum

Cruz-Torres et al. Nature Physics (2021)

Theory tells us we can factorize the system:

Pair Interaction



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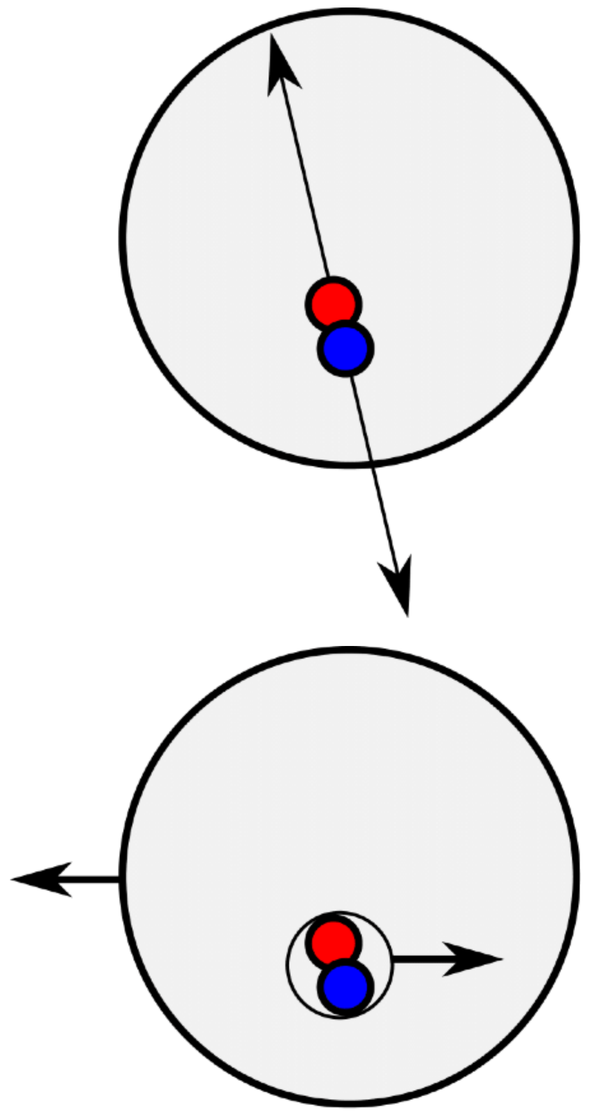
Pair Interaction

Center-of-Mass



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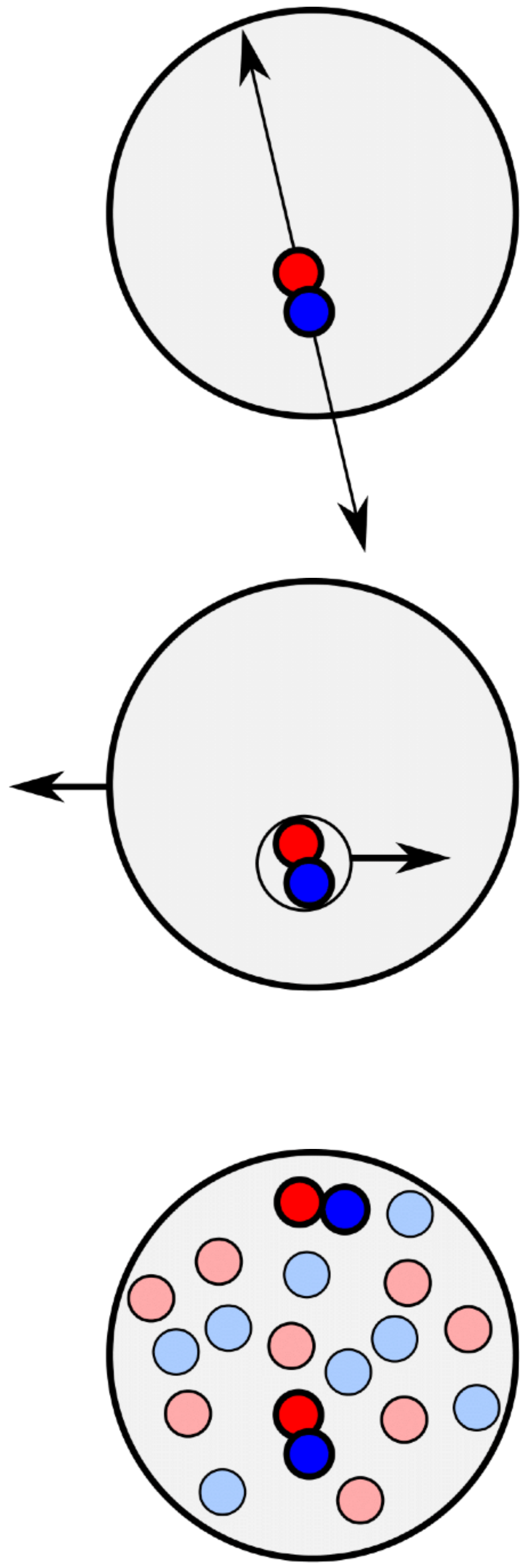
Theory tells us we can factorize the system:

Pair Interaction

Center-of-Mass

Pair Abundance



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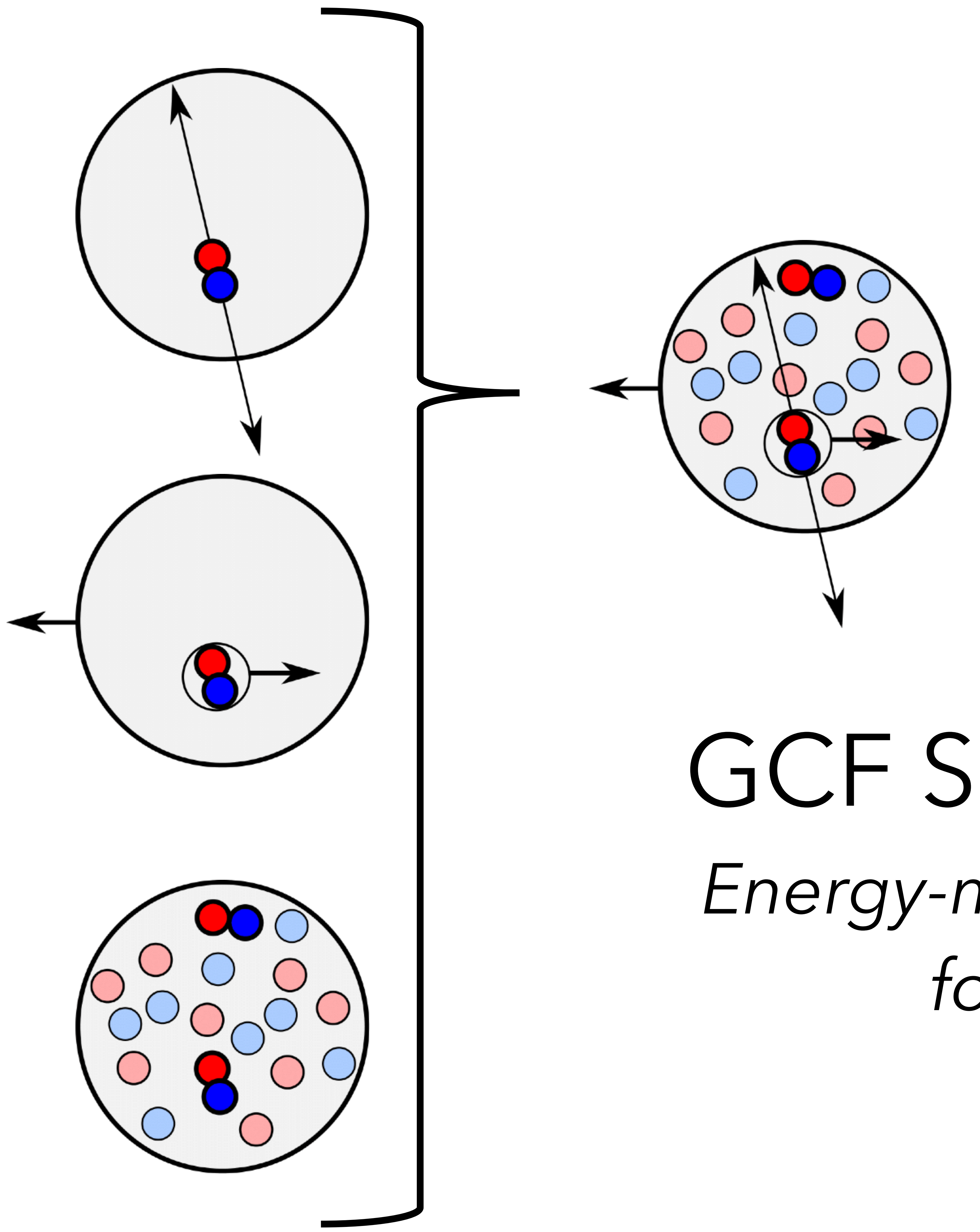

GCF Spectral Function

Energy-momentum distribution for SRC nucleons

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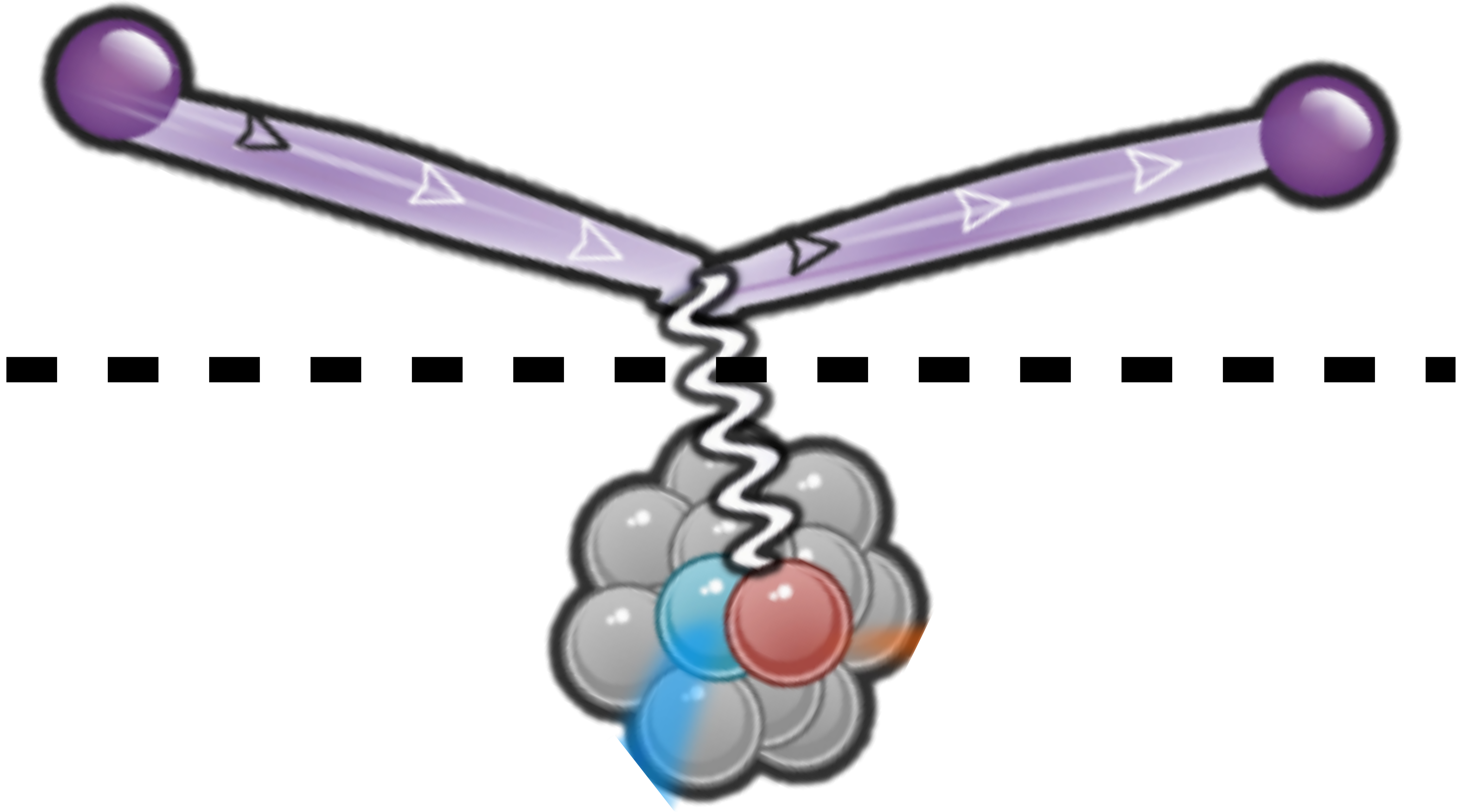
The Plane-Wave Impulse Approximation

Large momentum-transfer scattering → another separation of scales!

Factorized cross section model allows *direct comparison* between experiment and theory

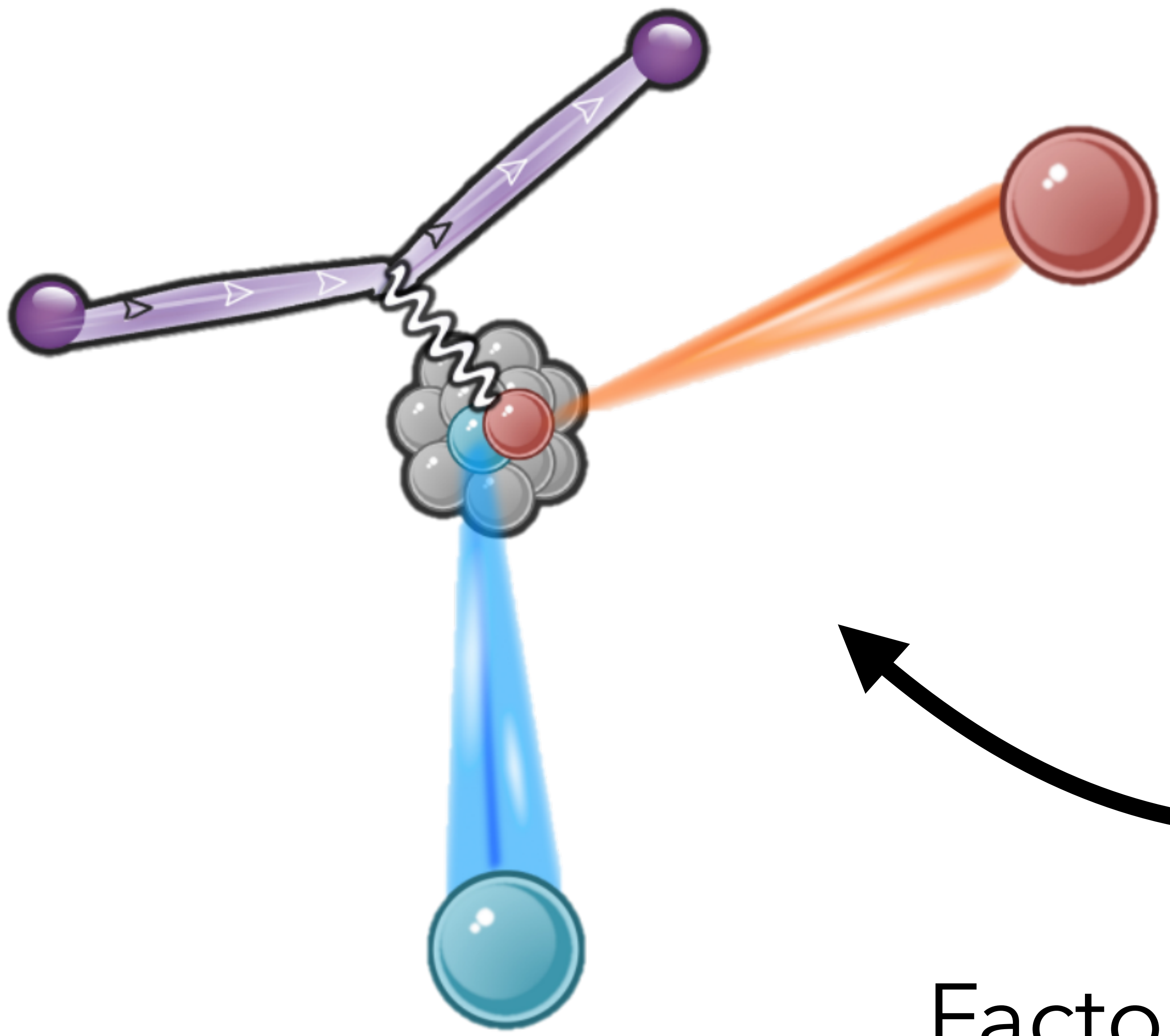


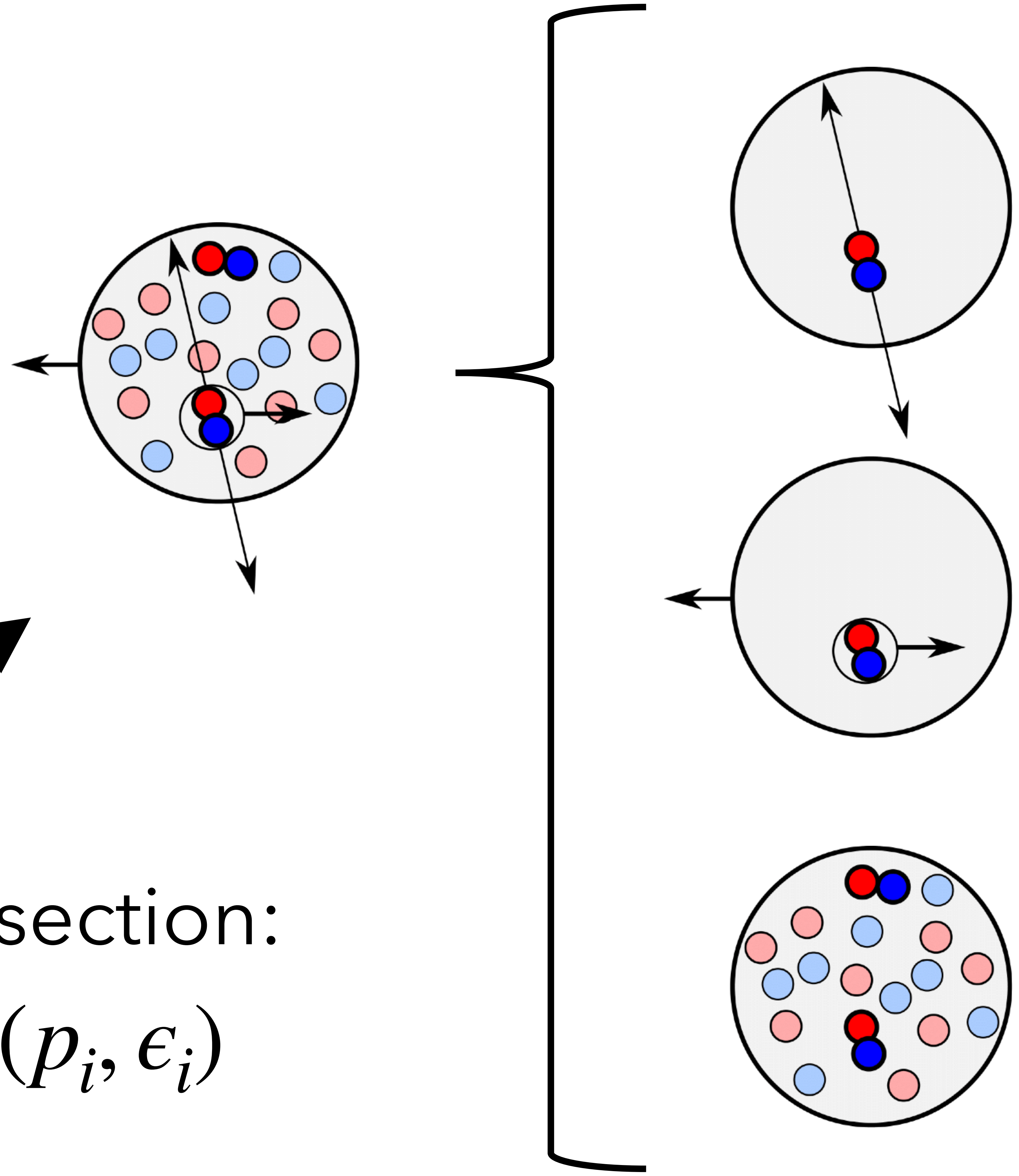
High-energy **Reaction**

$$\sigma \sim \sigma_{e,N}(q) \times S(p_i, \epsilon_i)$$

Low-energy **Ground-State**

With a solid model, we can use scattering data to make **quantitative** connections to SRC properties





Factorized cross section:

$$\sigma = \sigma_{e,N}(q) \times S(p_i, \epsilon_i)$$

Generalized Contact Formalism

$$S^p(p,\epsilon) = C_A^{pn,s=1}\cdot S_{pn}^{S=1}(p,\epsilon) + C_A^{pn,s=0}\cdot S_{pn}^{S=0}(p,\epsilon) + 2C_A^{pp,s=0}\cdot S_{pp}^{S=0}(p,\epsilon)$$

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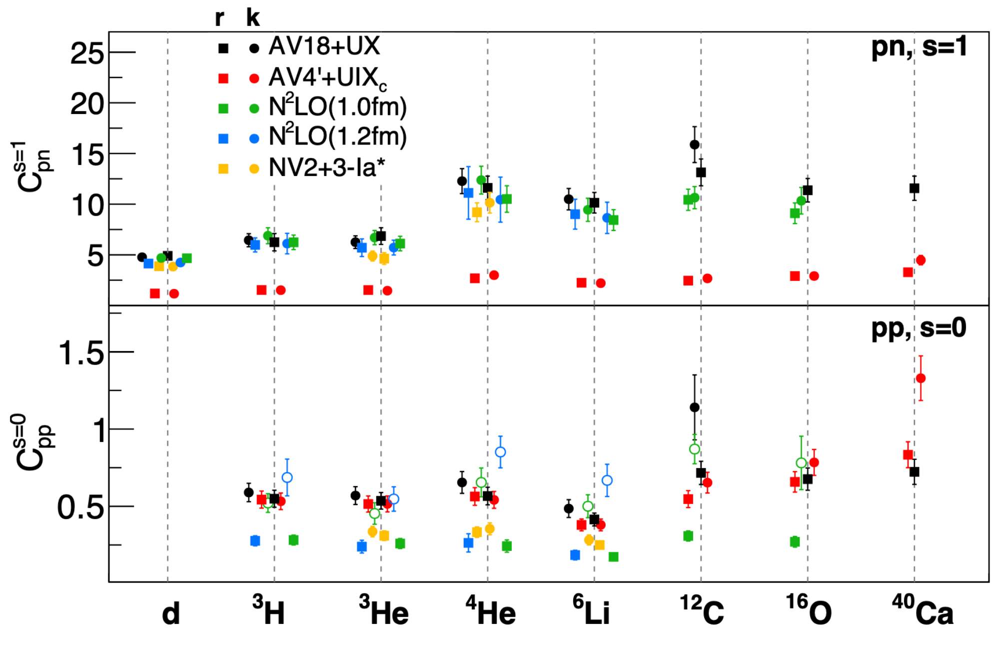
Each pair convolves relative and CM motion:

$$S_{ab}^{\alpha}(p_1,E_1) = \frac{1}{4\pi}\int \frac{d^3p_2}{(2\pi)^3}\delta\Big[f(p_2)\Big]\Big|\phi_{ab}^{\alpha}\big((\vec{p}_1-\vec{p}_2)/2\big)\Big|^2 n_{ab}^{\alpha}(\vec{p}_1+\vec{p}_2)$$

Relative **CM**

Generalized Contact Formalism



Ab-initio SRC abundances

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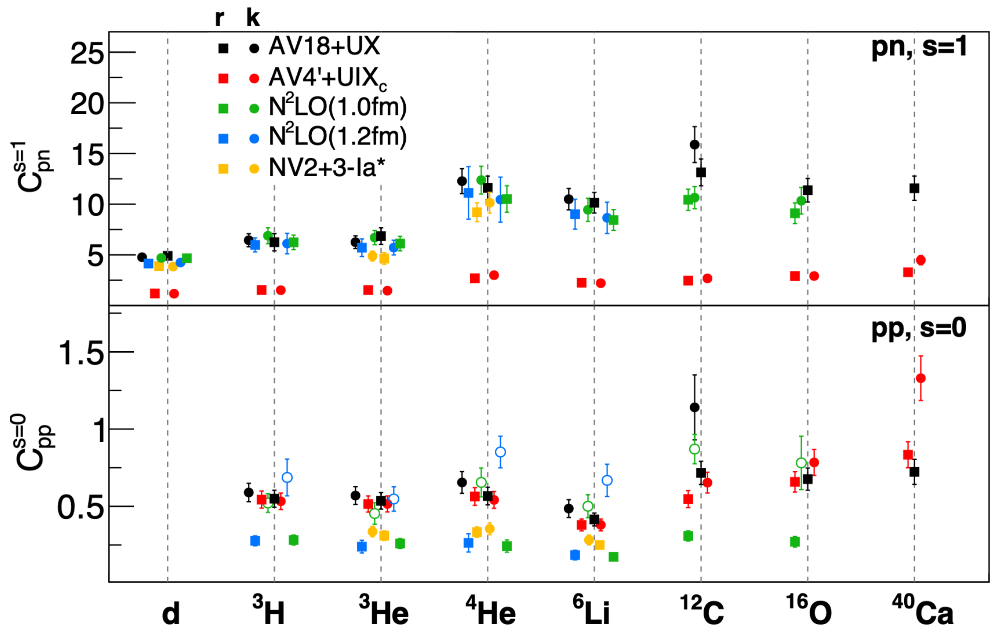

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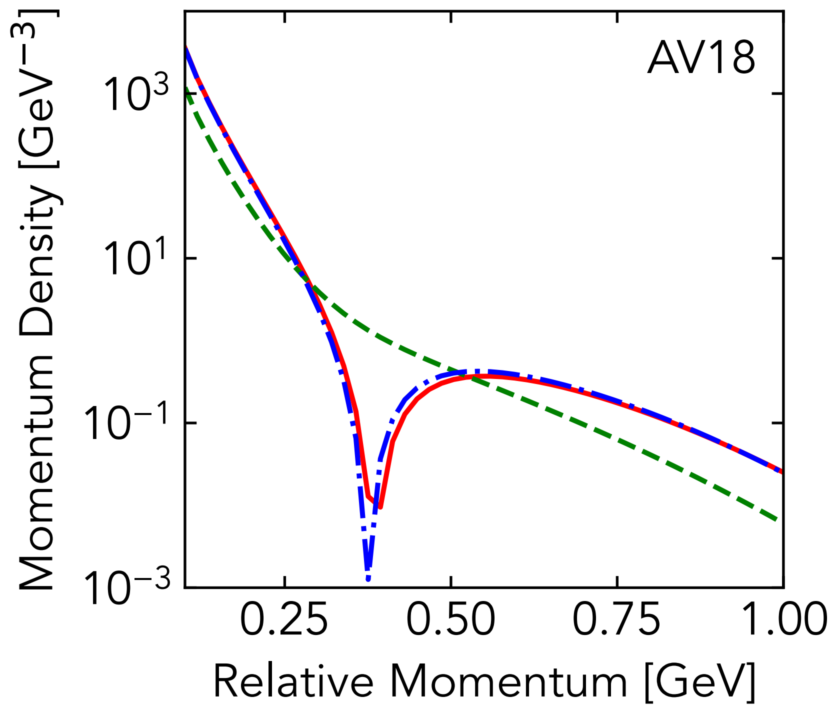

AV18 / N2LO / …

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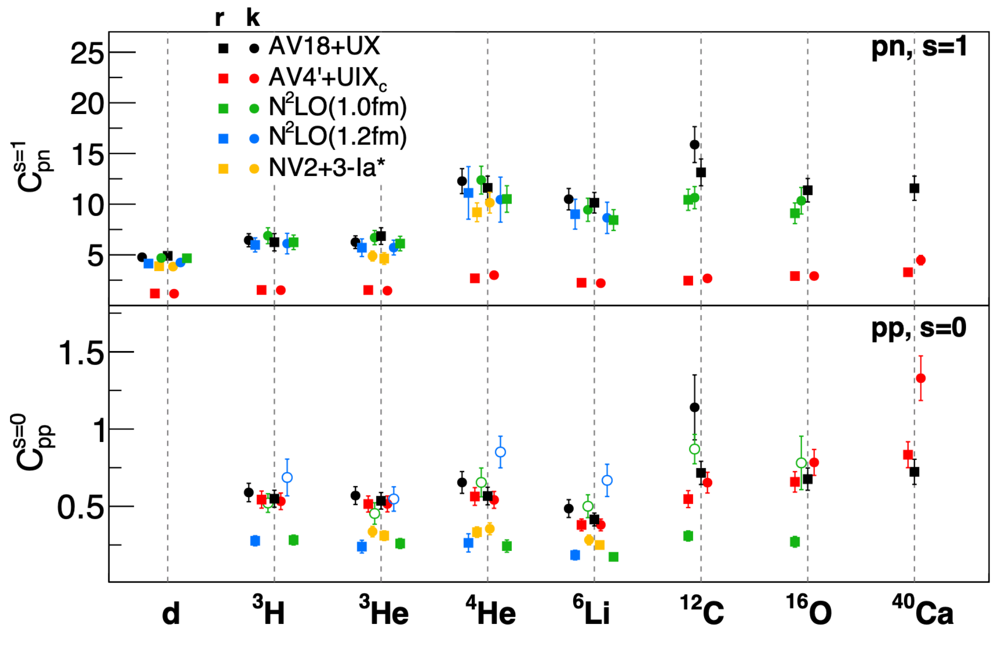

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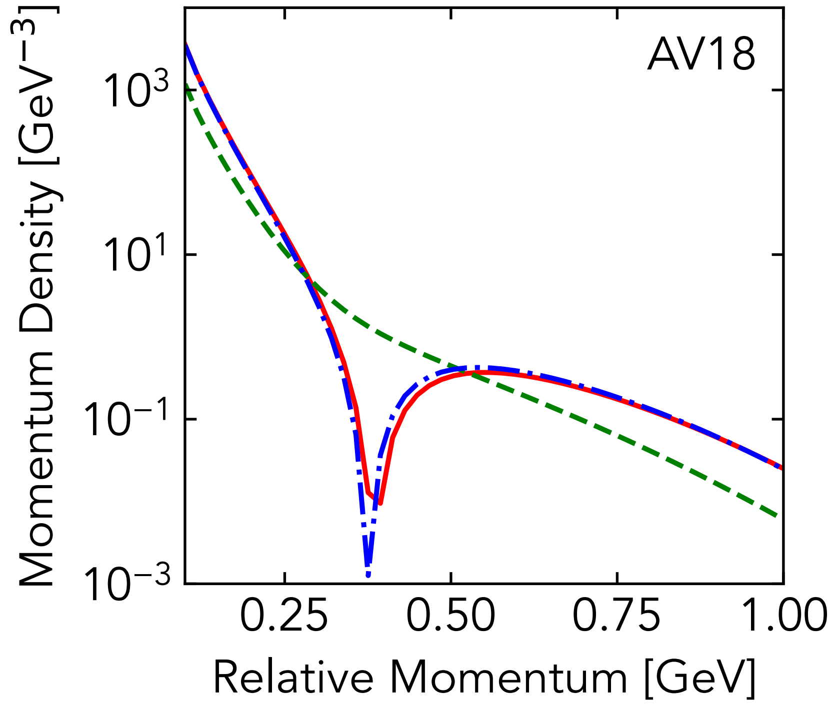
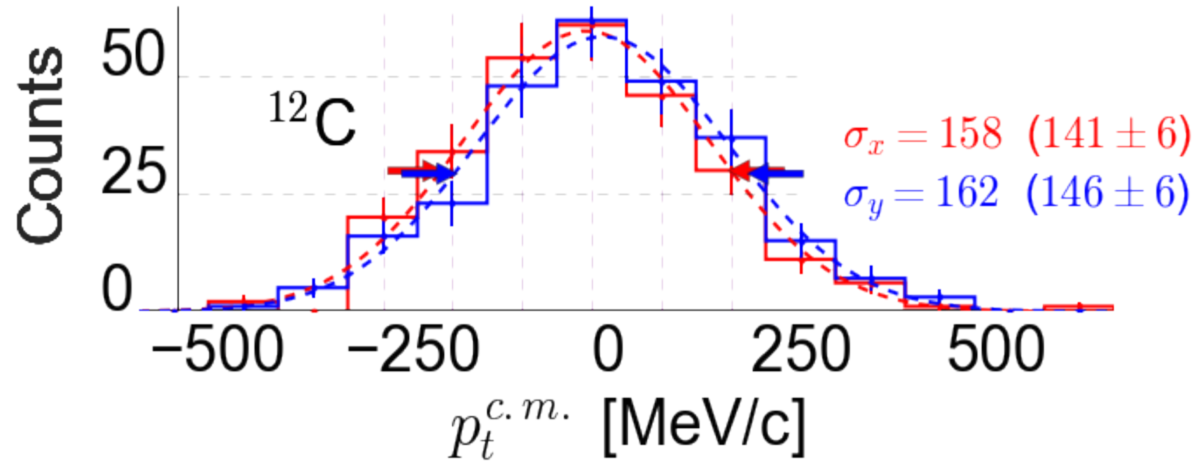


AV18 / N2LO / …

Gaussian – experimental extraction



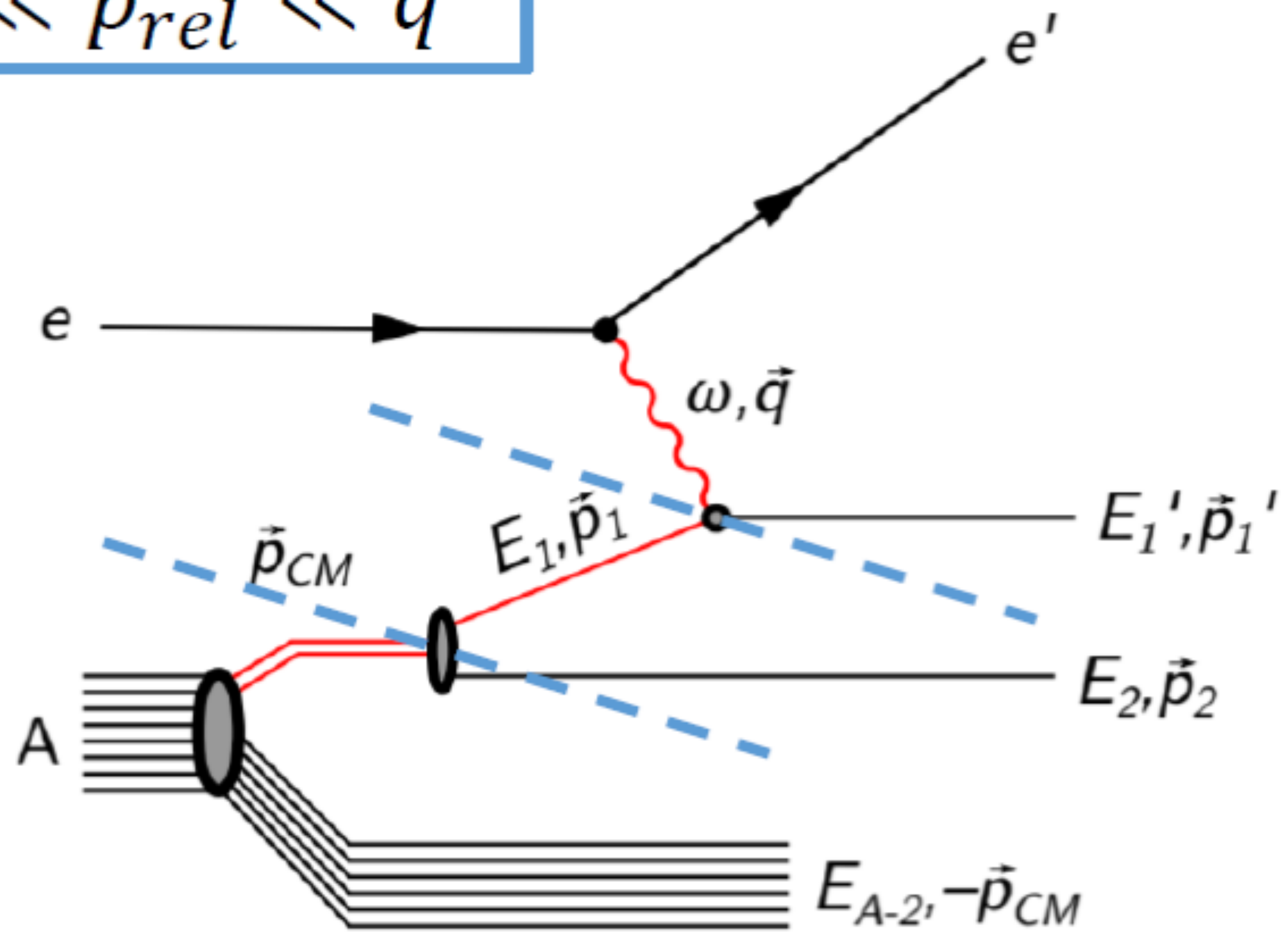
Generalized Contact Formalism

$$p_{CM} \ll p_{rel} \ll q$$

$$\sigma = K \cdot \sigma_{eN} \cdot D(p_i, p_{rec})$$

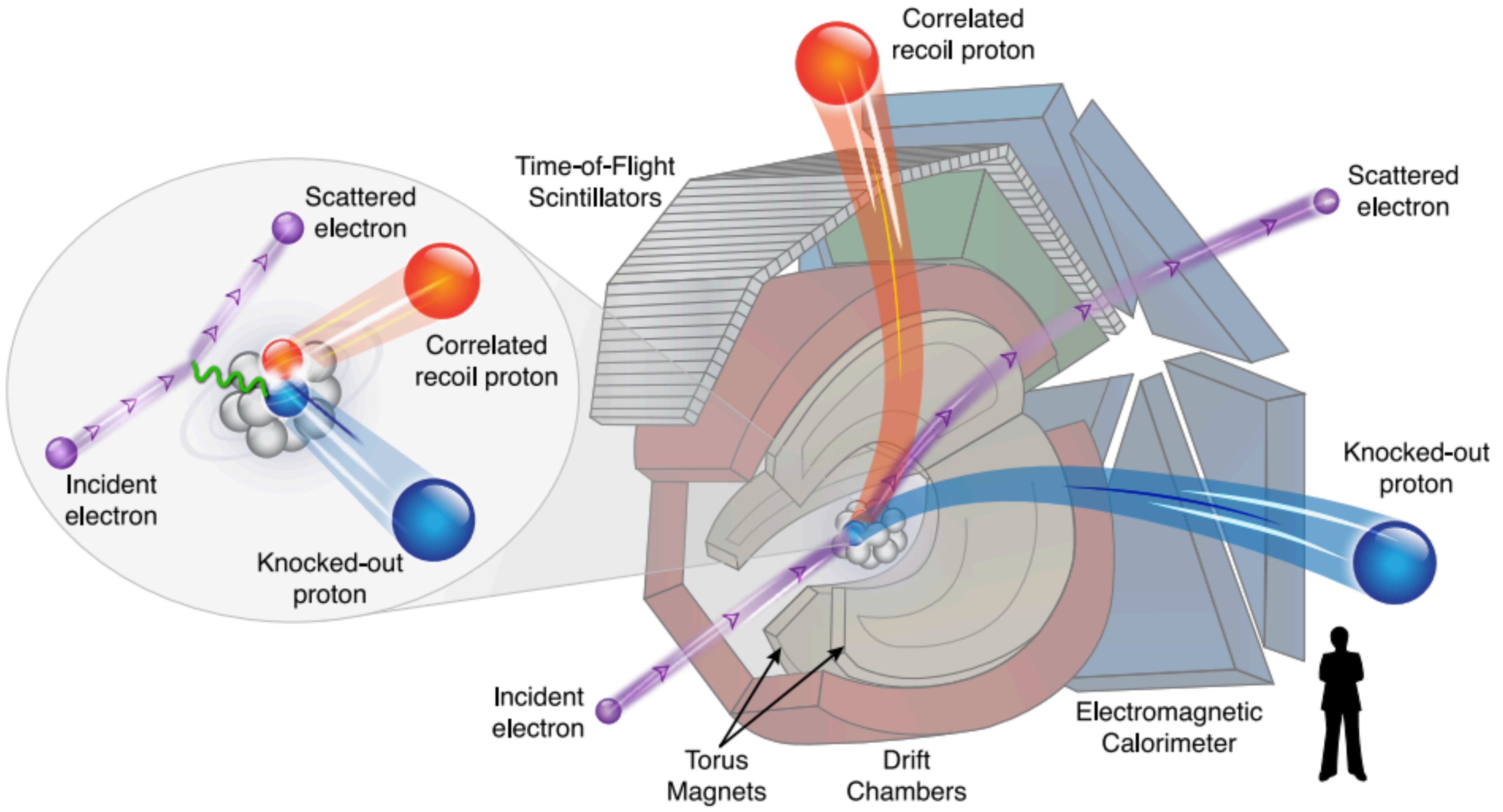
GCF Factorization

$$D(p_i, p_{rec}) = n(p_{CM}) \sum_i C_i \,|\, \phi_i(p_{rel}) \,|^2$$

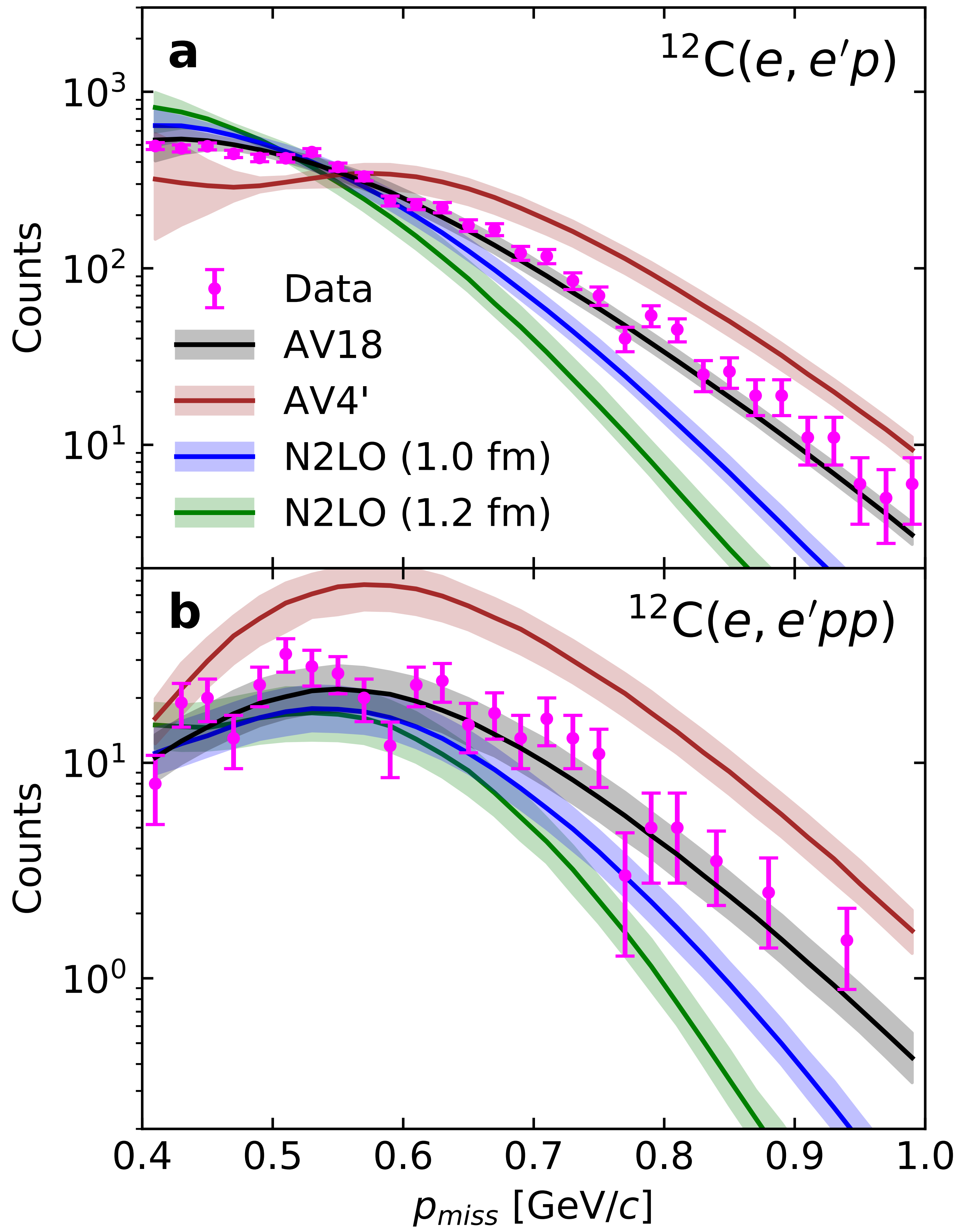


Compare theory to CLAS EG2 Experiment

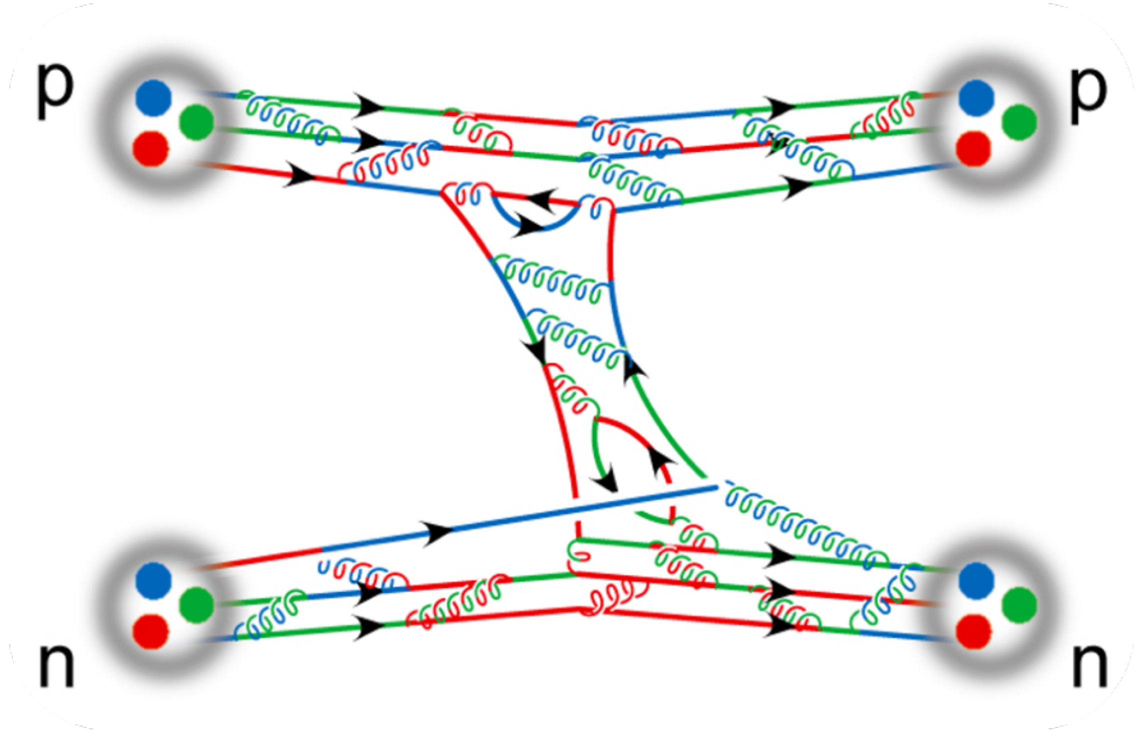
- Jefferson Lab Hall B
- 5-GeV e^- beam
- C, Al, Fe, Pb
- Large-acceptance detector
- Measuring $(e, e'p)$, $(e, e'pp)$, $(e, e'pn)$

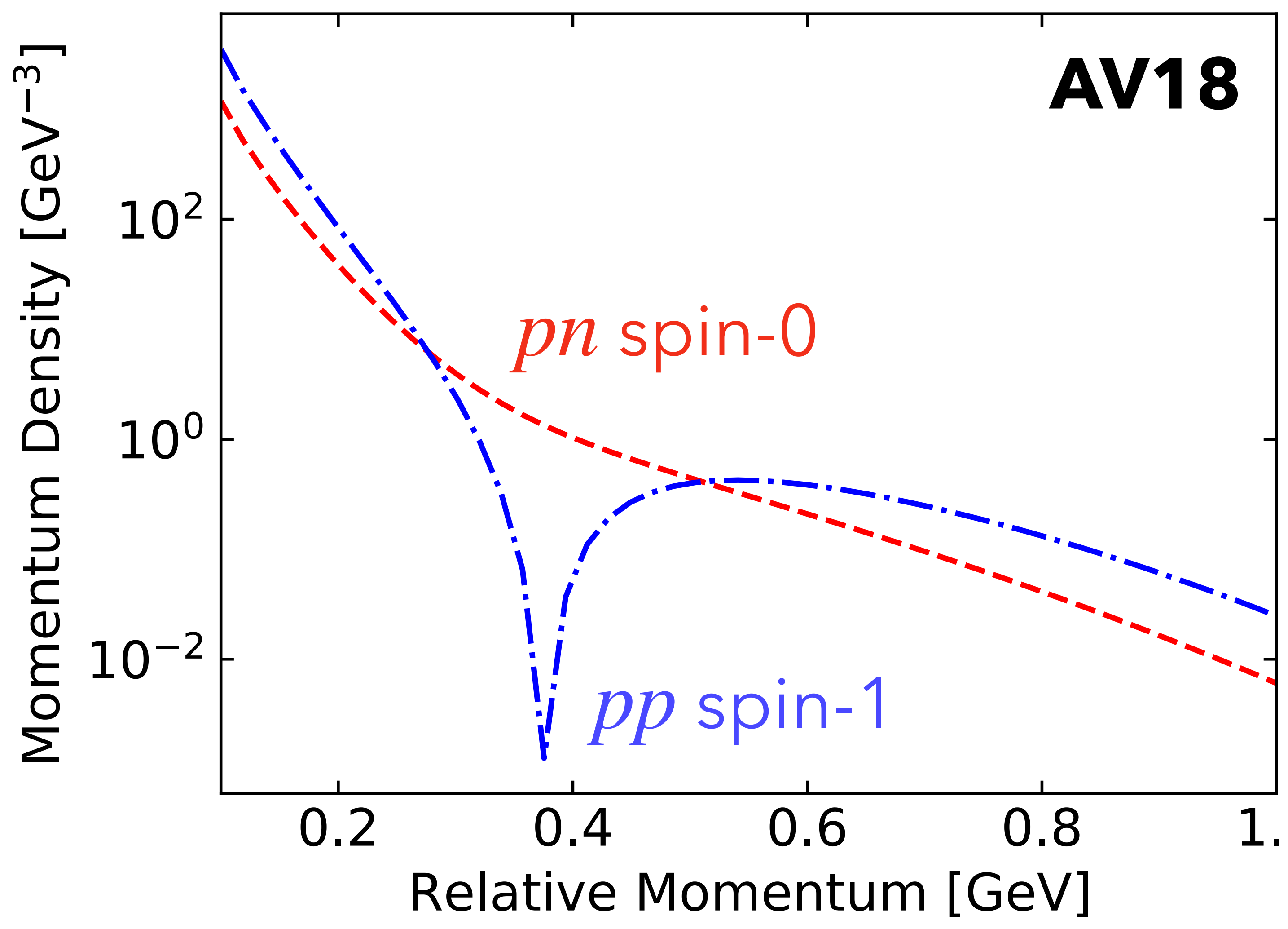


Missing momentum distribution connects to short-distance NN interaction



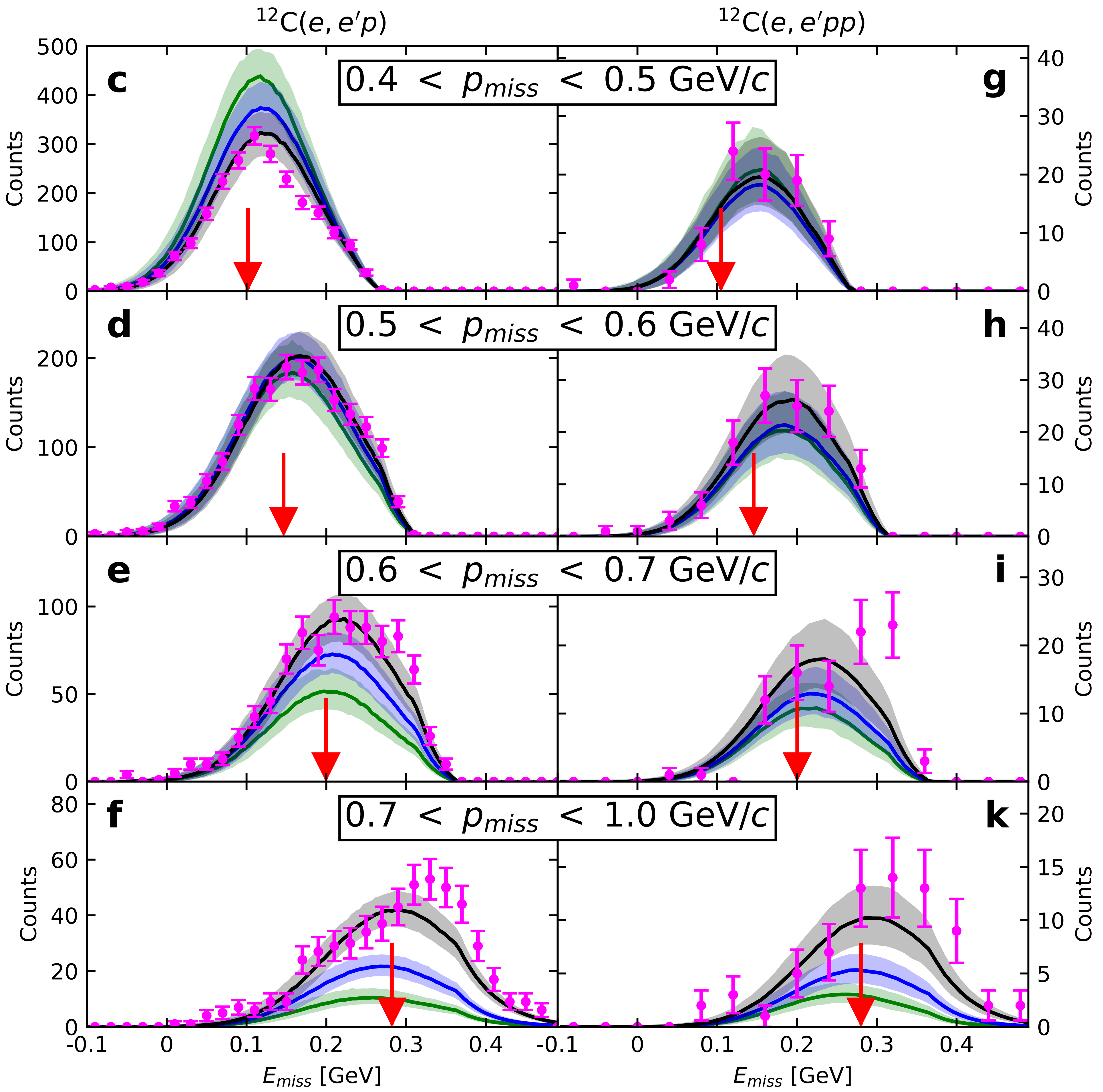
Different NN models = different predictions at high p_{miss}

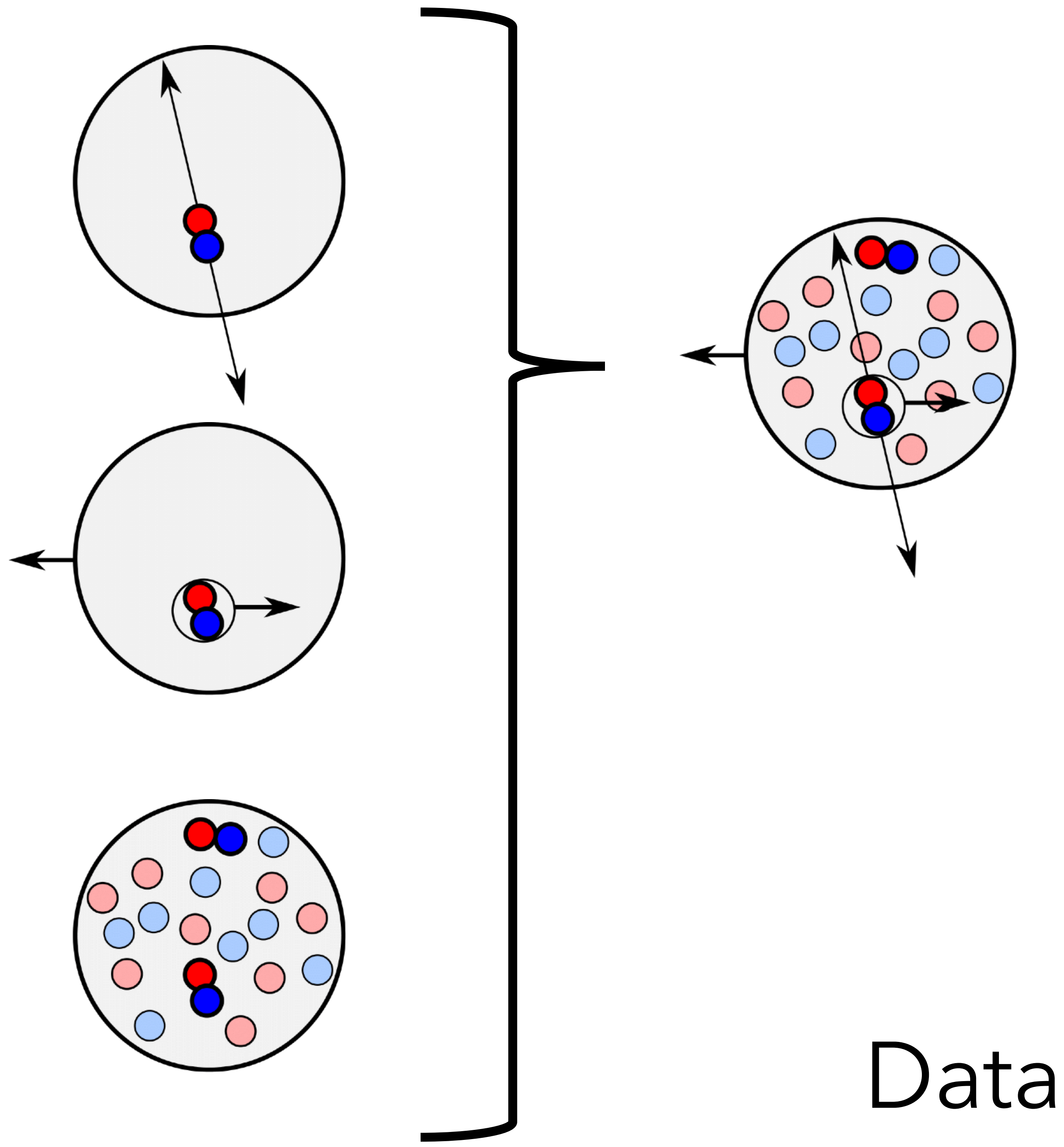




Schmidt et al. Nature (2020)

Factorized GCF model captures momentum-energy correlations

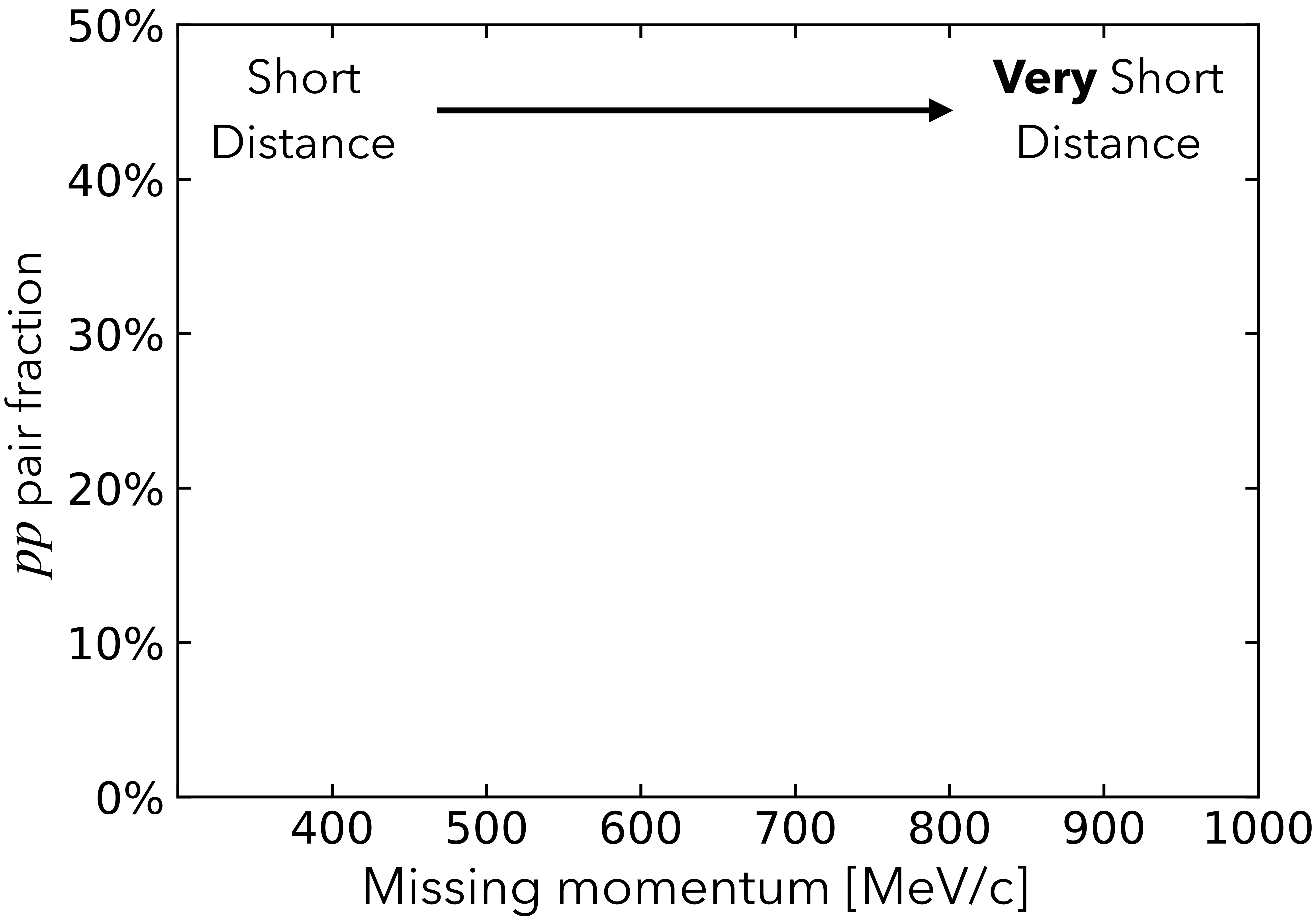




Data validate use of factorized convolution model

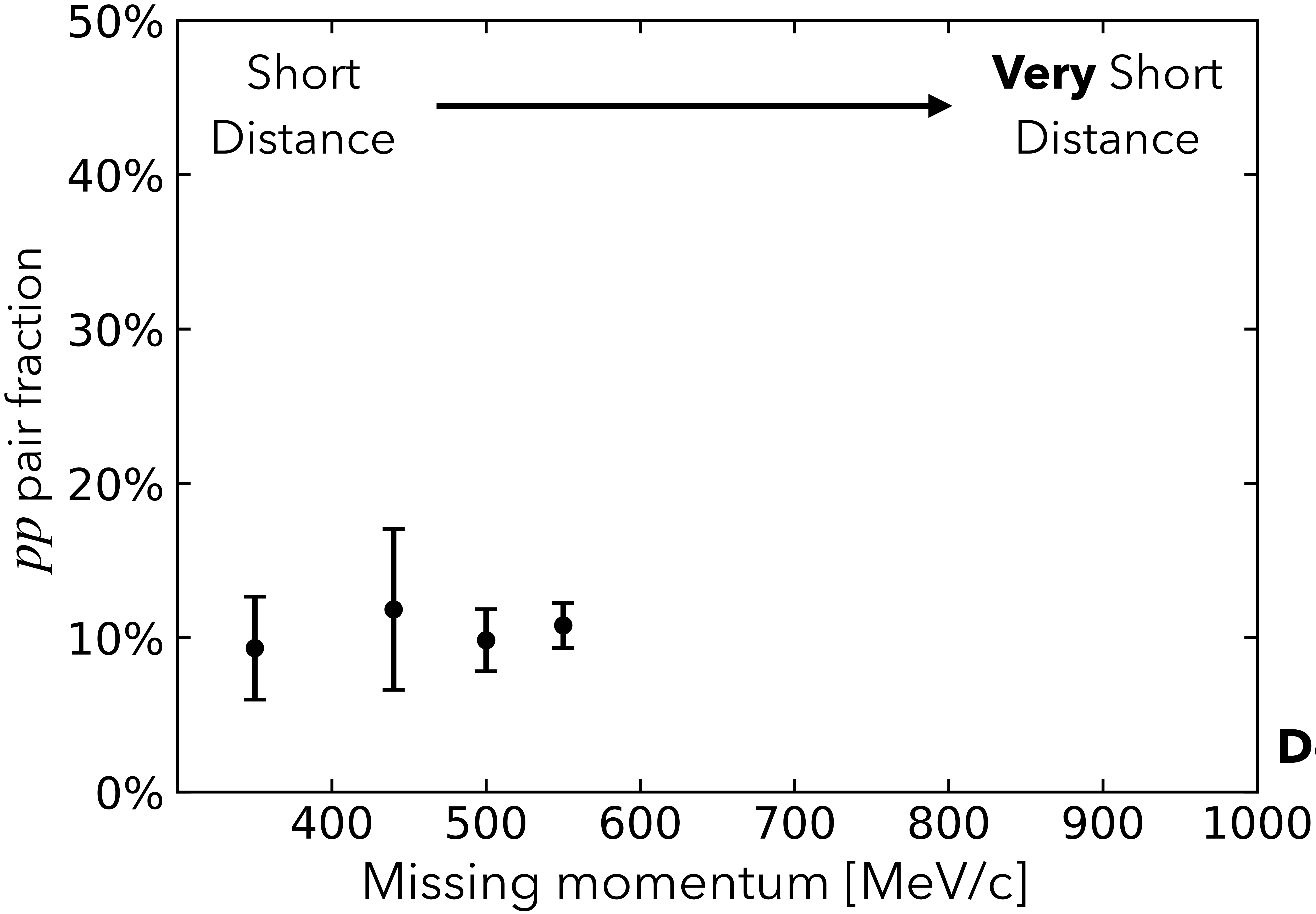
Schmidt et al. Nature (2020)

Probing the core of the NN interaction



Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

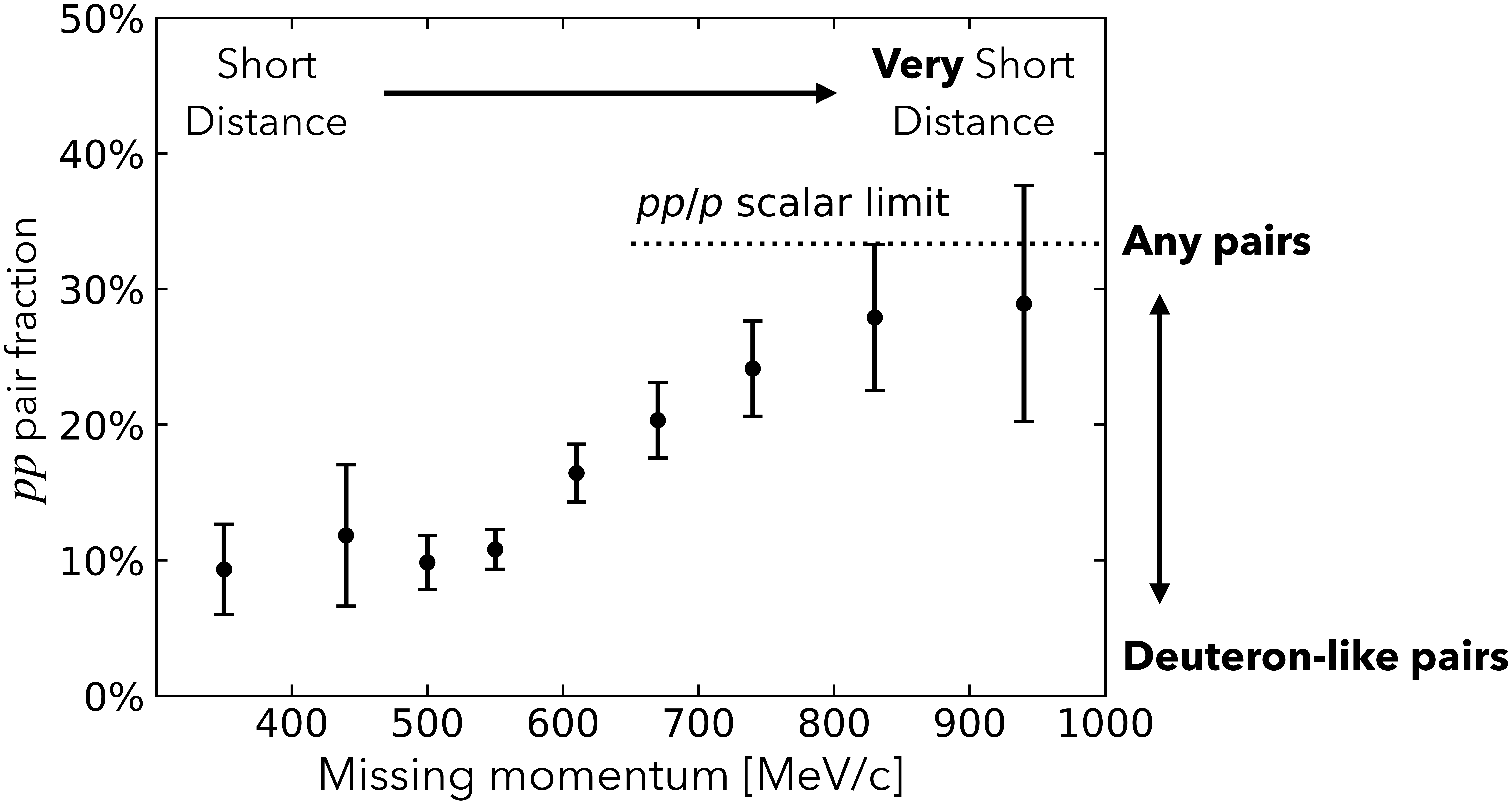
Probing the core of the NN interaction



Deuteron-like pairs

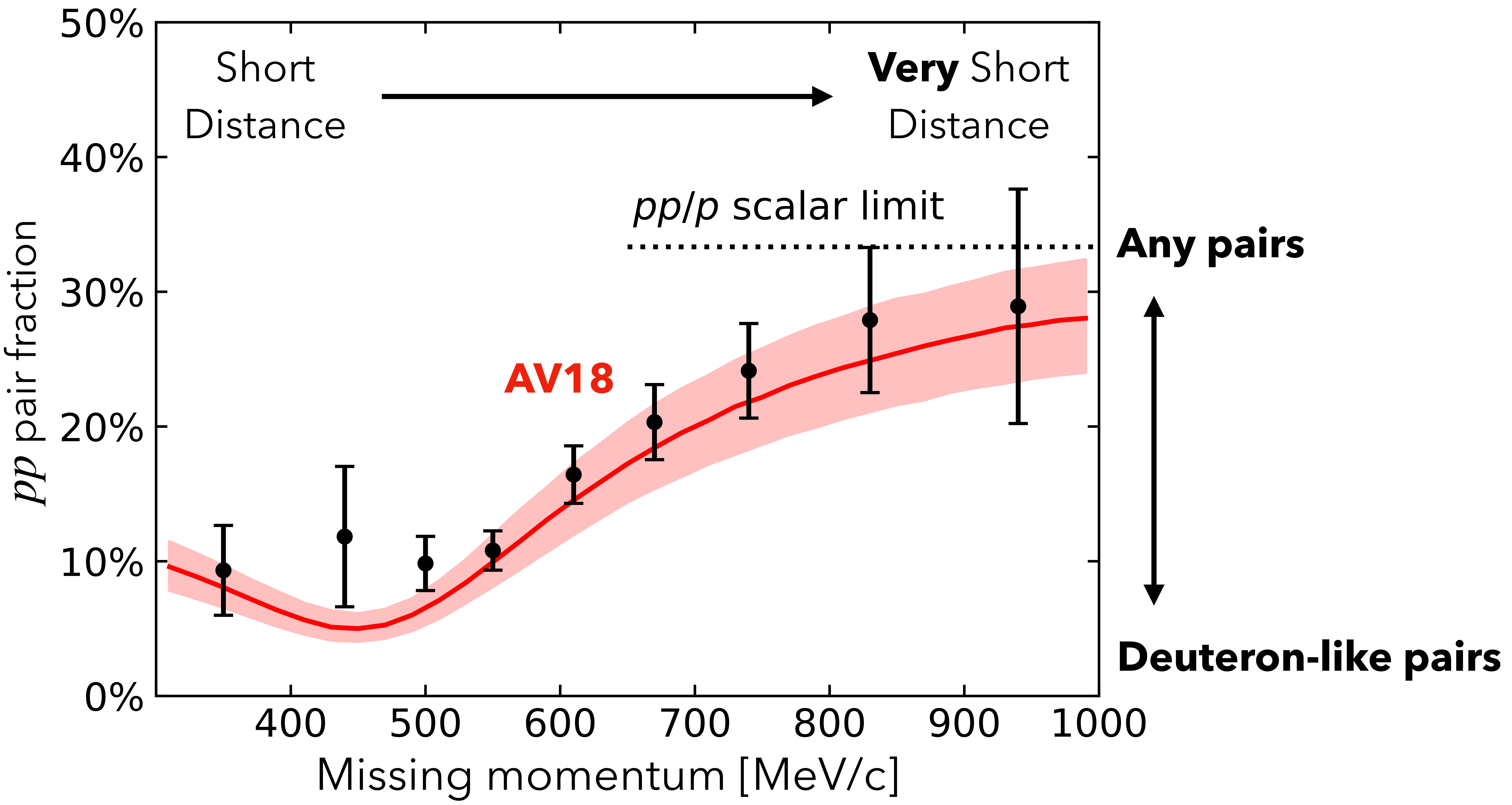
Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

Probing the core of the NN interaction



Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

Probing the core of the NN interaction



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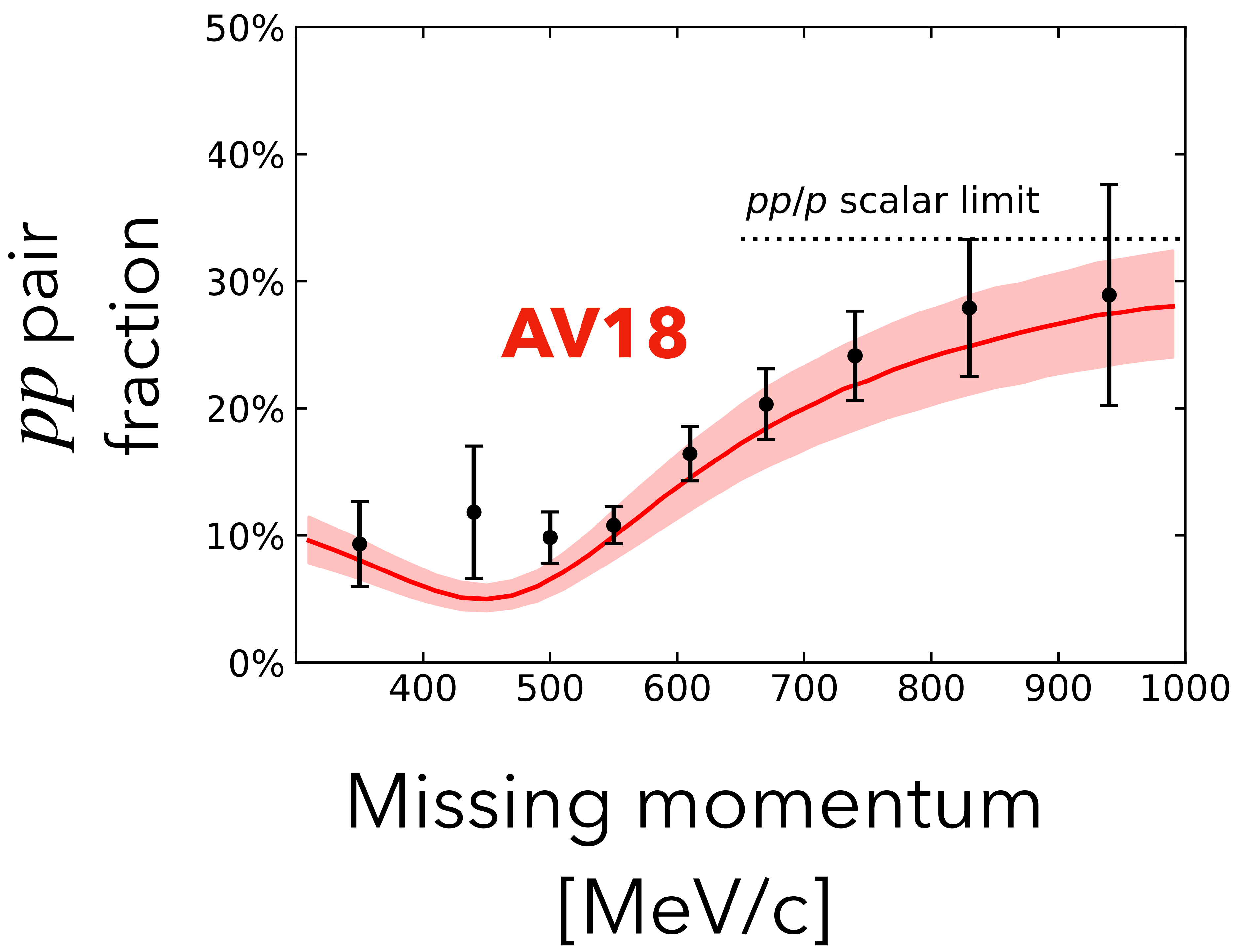
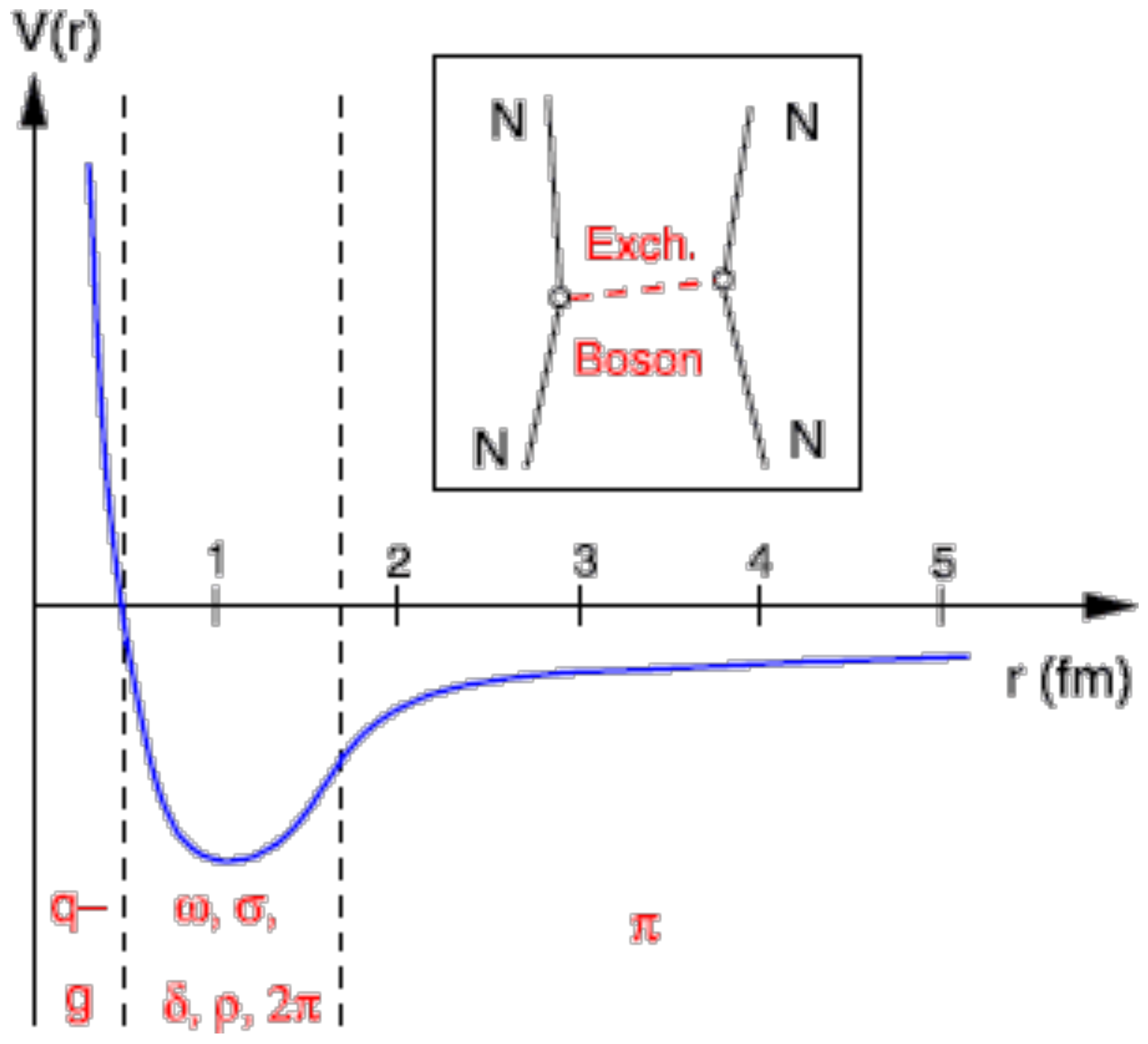
Probing the core of the NN interaction



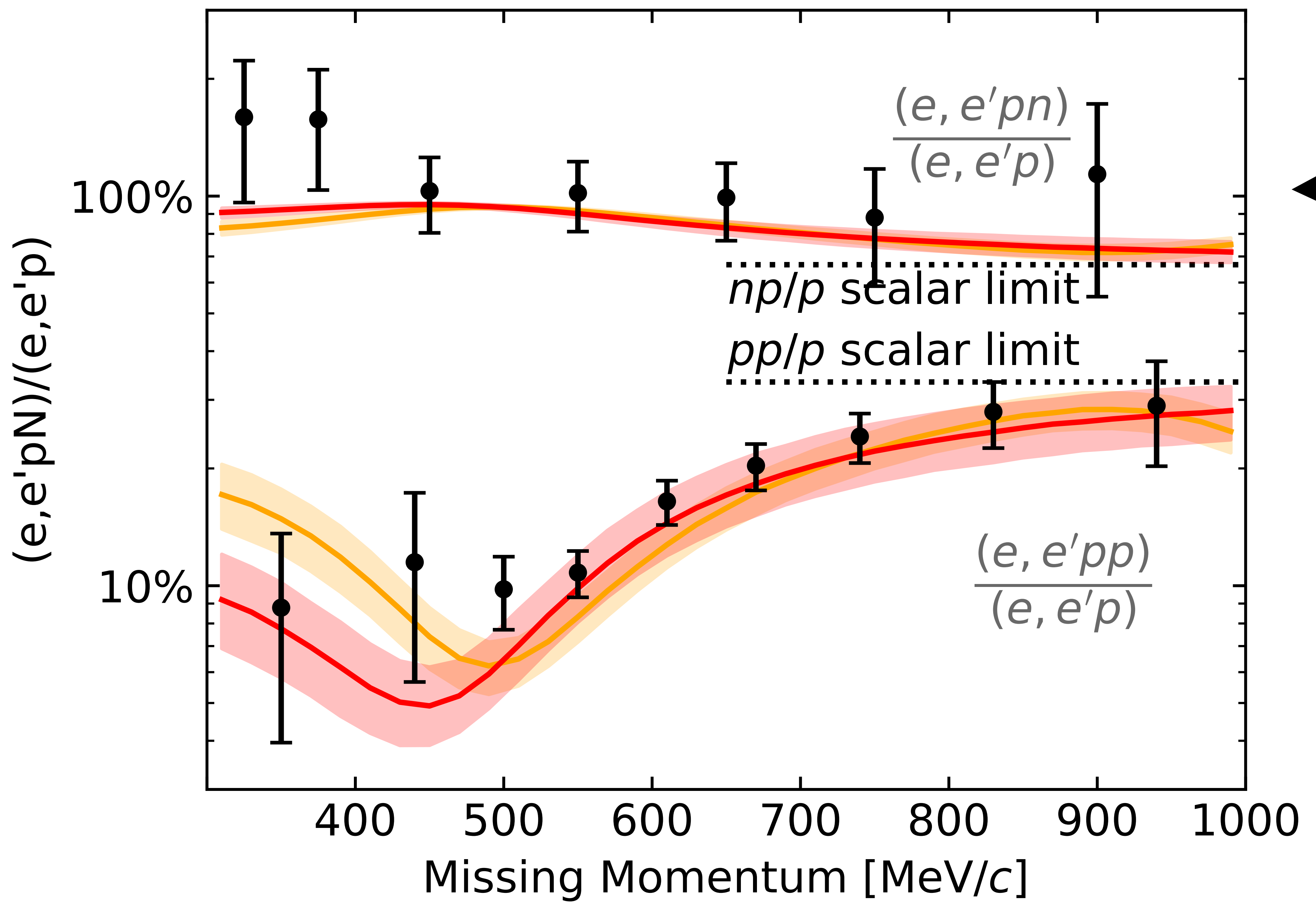


Repulsive scalar core

Tensor-dominated

Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

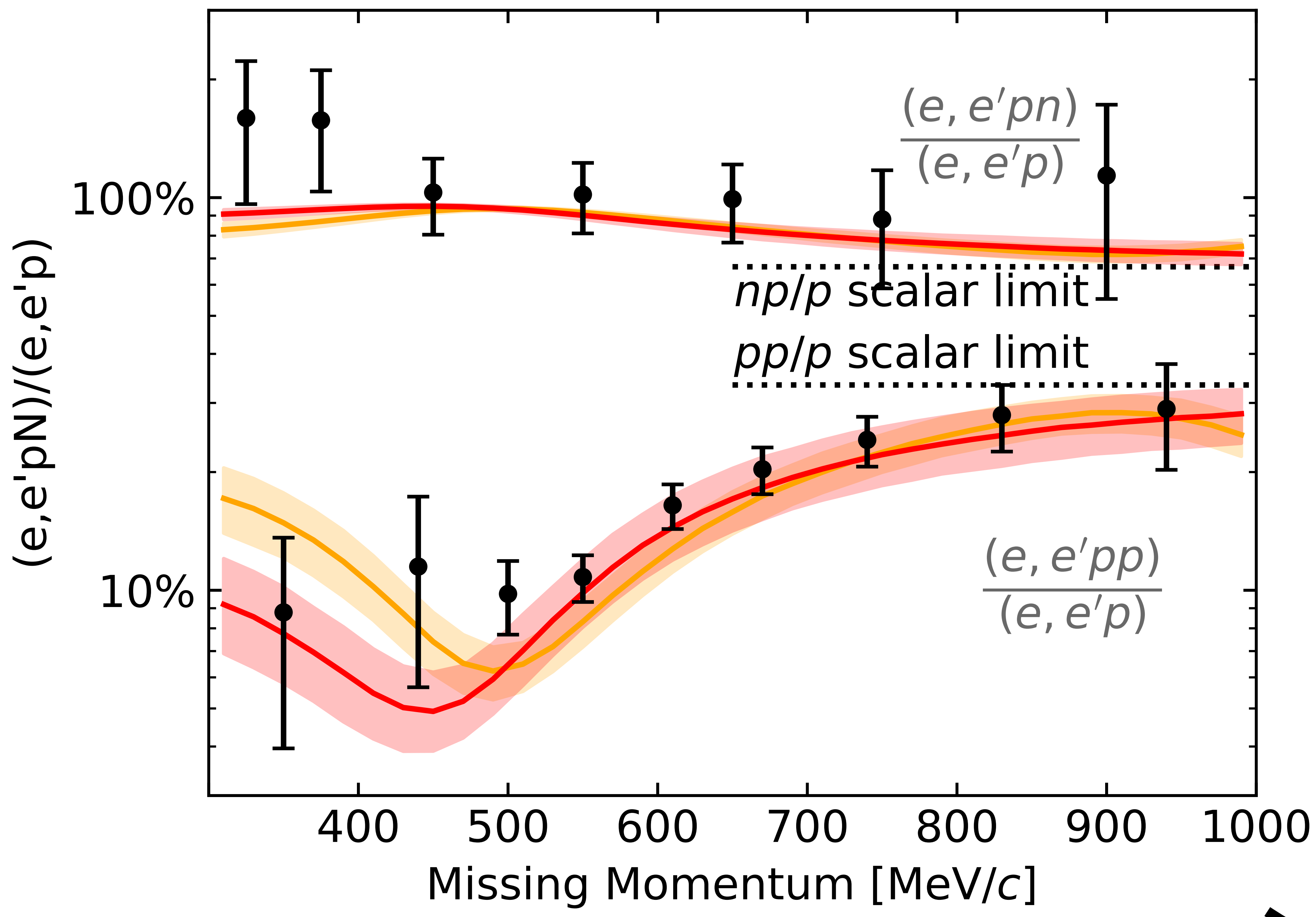
High-Momentum SRC Dominance

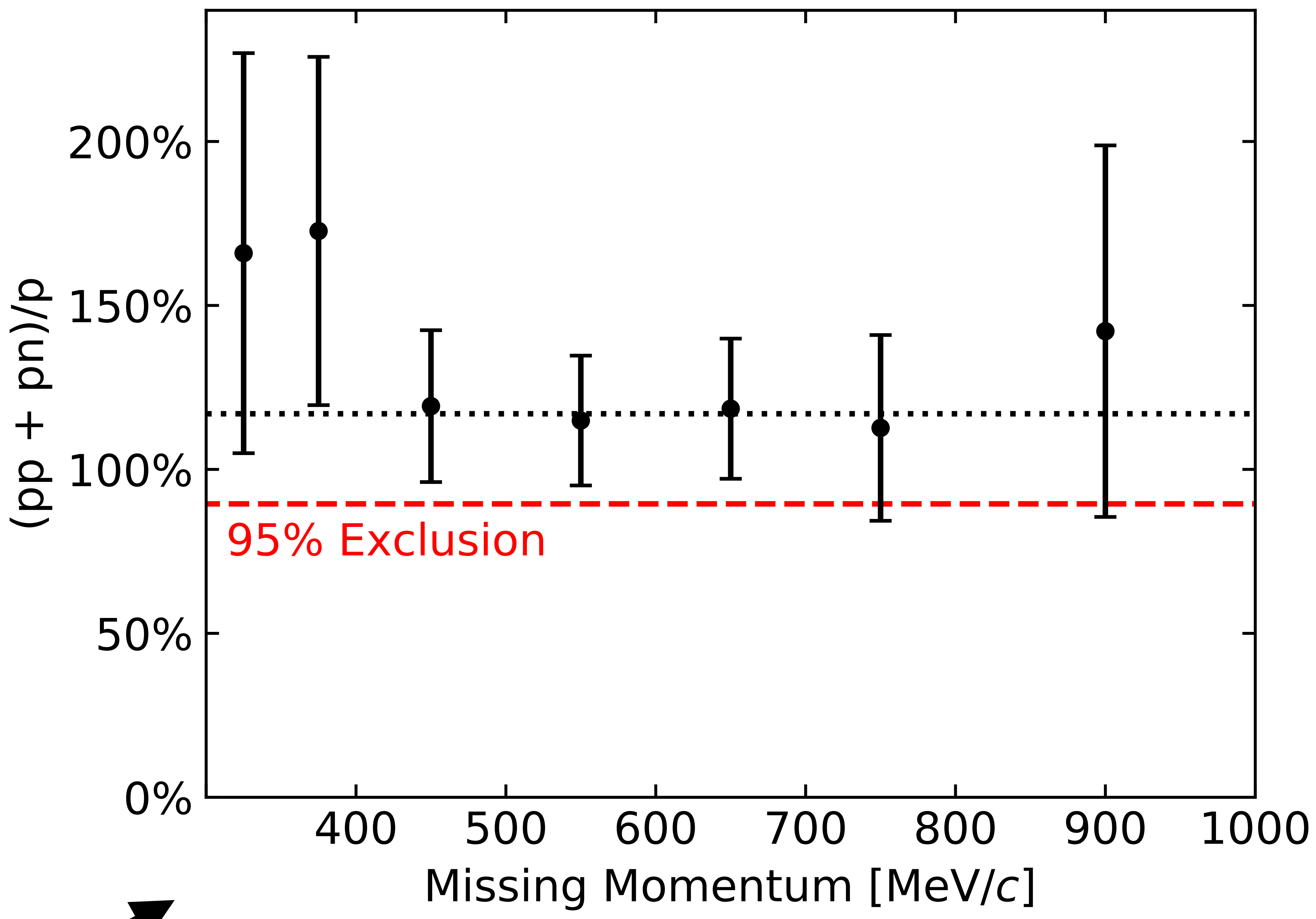


Adding recoil neutron detection gives complete picture of SRC isospin structure

Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

High-Momentum SRC Dominance

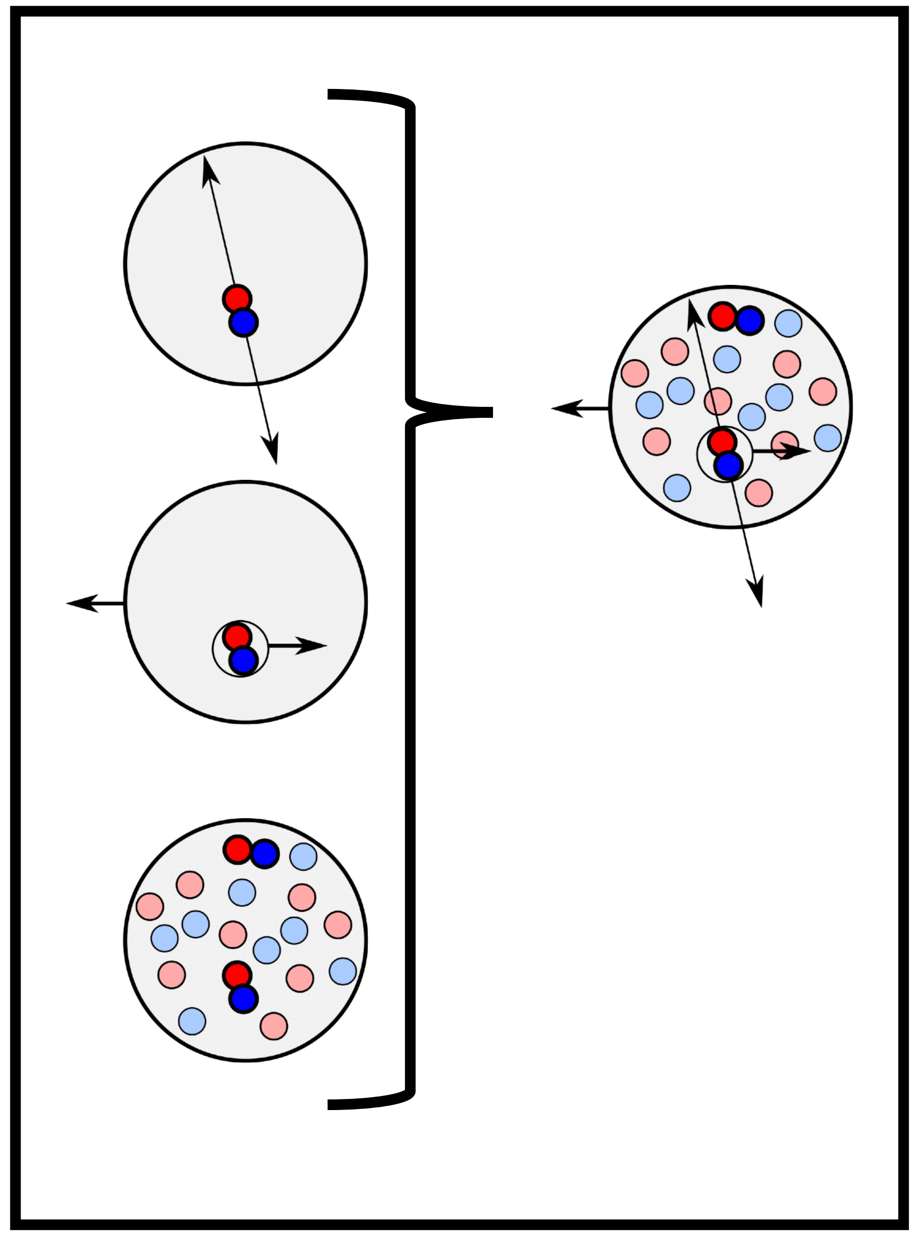




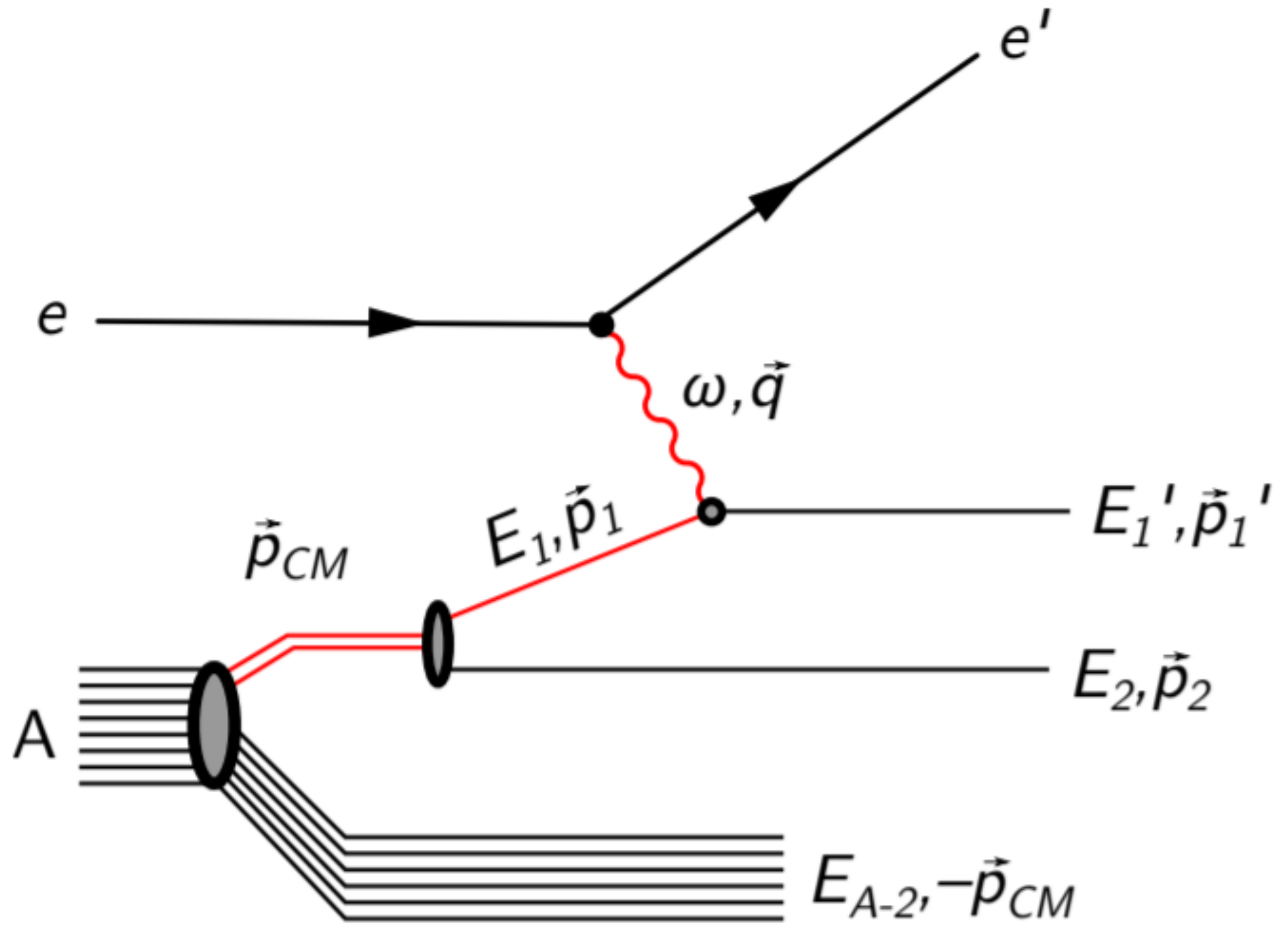
At least 90% of high-momentum protons have a partner

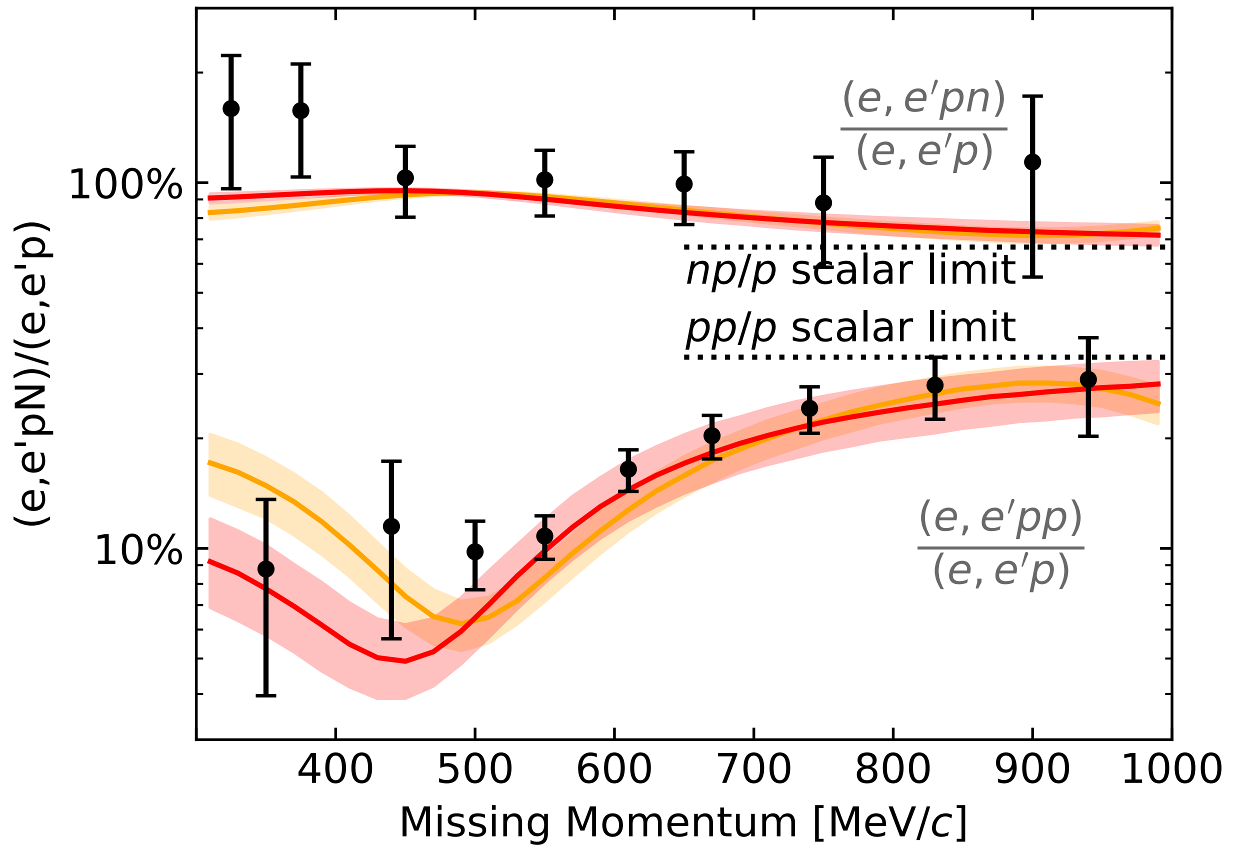
Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

GCF analysis connect scattering data to ground-state SRC properties



$$\frac{d^6\sigma}{d\Omega_k dE_k d^3p_1'} = \mathcal{J}\sigma_{eN}S^N(p_1,\epsilon_1)$$



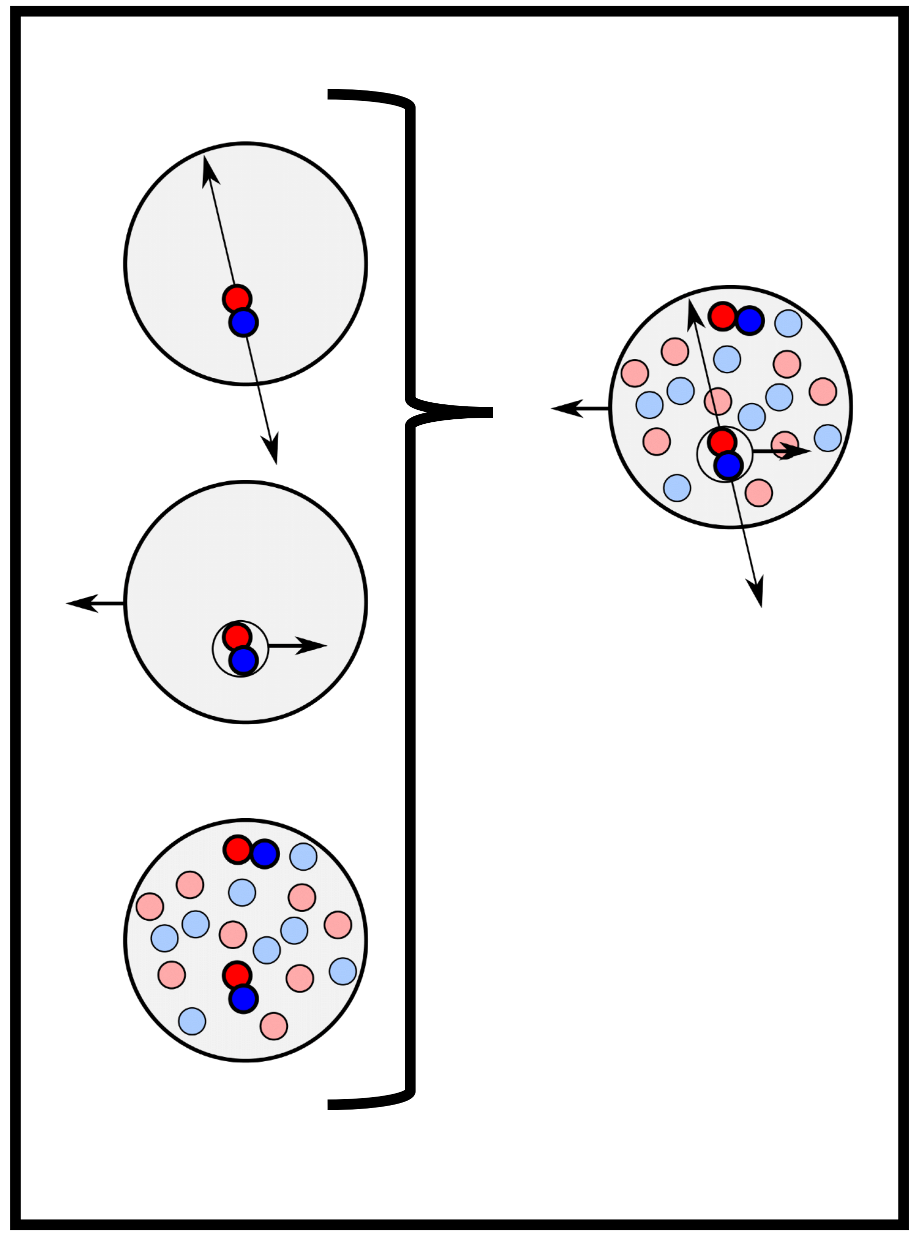


SRC properties relate to GCF spectral function

GCF cross section can be directly compared to measured data

Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

GCF analysis connect scattering data to ground-state SRC properties



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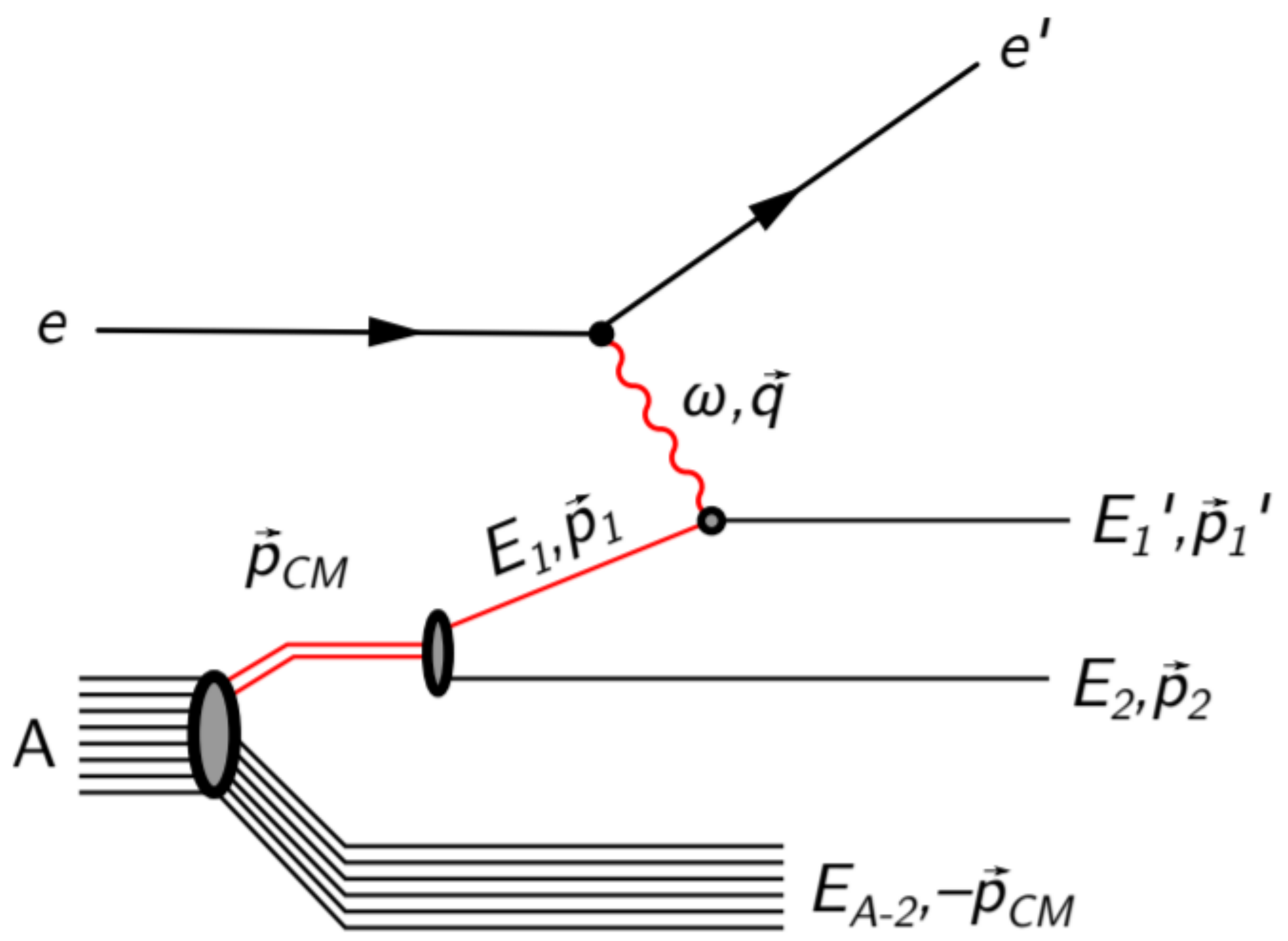

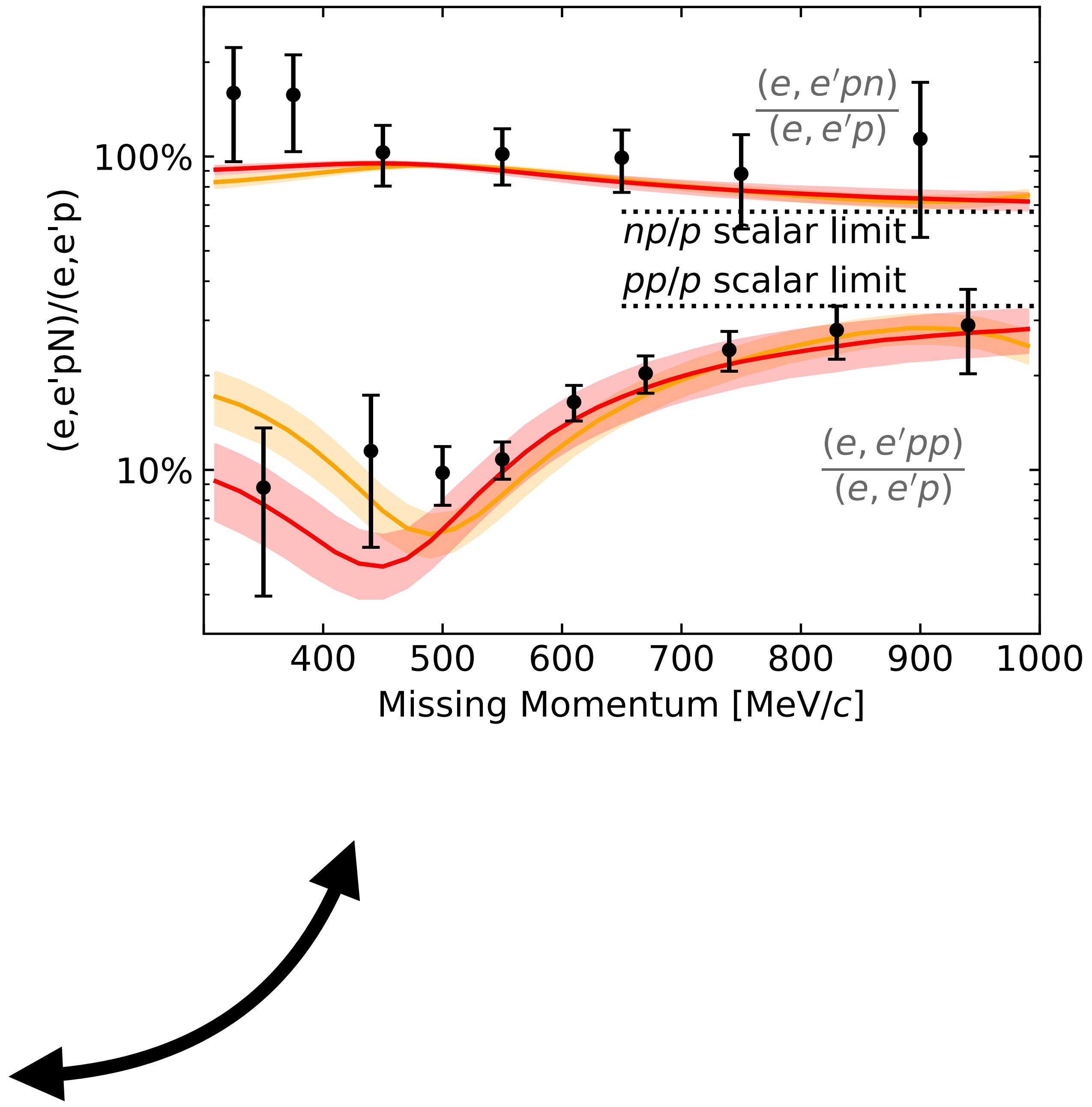

SRC properties relate to GCF spectral function

Rely on high-resolution framework:

$$\sqrt{Q^2} \gg p_{miss}$$

GCF cross section can be directly compared to measured data

Schmidt et al. Nature (2020)
Pybus et al. PLB (2020)
Korover et al. PLB (2021)

Up next: Establishing the connection between experimental data and the nuclear wavefunction